Neutrino Cross Sections
Past, Present, and Future

NuInt04

Sep.26-29,2005
NuInt05
Okayama Univ.

NUINT'02

Sam Zeller
Columbia University

FNAL Wine & Cheese
June 1, 2007

- this week Fermilab has been host to NuInt07 workshop
  - 5th Int'l Workshop on ν-Nucleus Interactions in the Few-GeV Region
  - devoted solely to topic of **low energy neutrino cross sections**
  - hit some highlights … exciting time!

Outline

- **Motivation**
  - ν oscillations and open questions in ν physics
  - what are the ν cross sections most interested in?
  - provide a little bit of the history
- **Current & Future Experiments**
- **Neutrino Cross Sections Measurements**
  - experimental results on the various ν reactions
  - past, present, and future

Neutrino Oscillations

$$P_{12} = \sin^2 2\theta \, \sin^2 \frac{1.27 \, \Delta m^2 \, L}{E}$$

- current picture:
  3 ν's and 2 mass scales

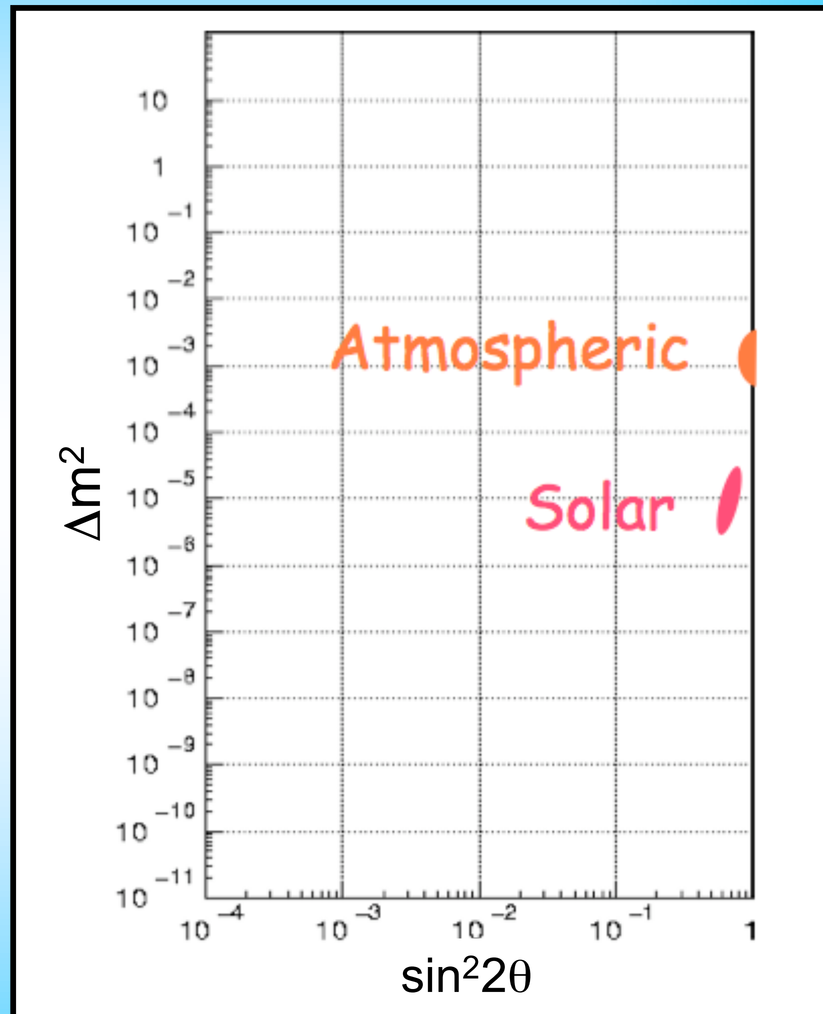
ν_3

$\Delta m^2_{ATM} \sim 10^{-3}$ eV^2

ν_2

$\Delta m^2_{SOL} \sim 10^{-5}$ eV^2

ν_1



(C. Walter, NuInt07)

- this is the world we currently live in

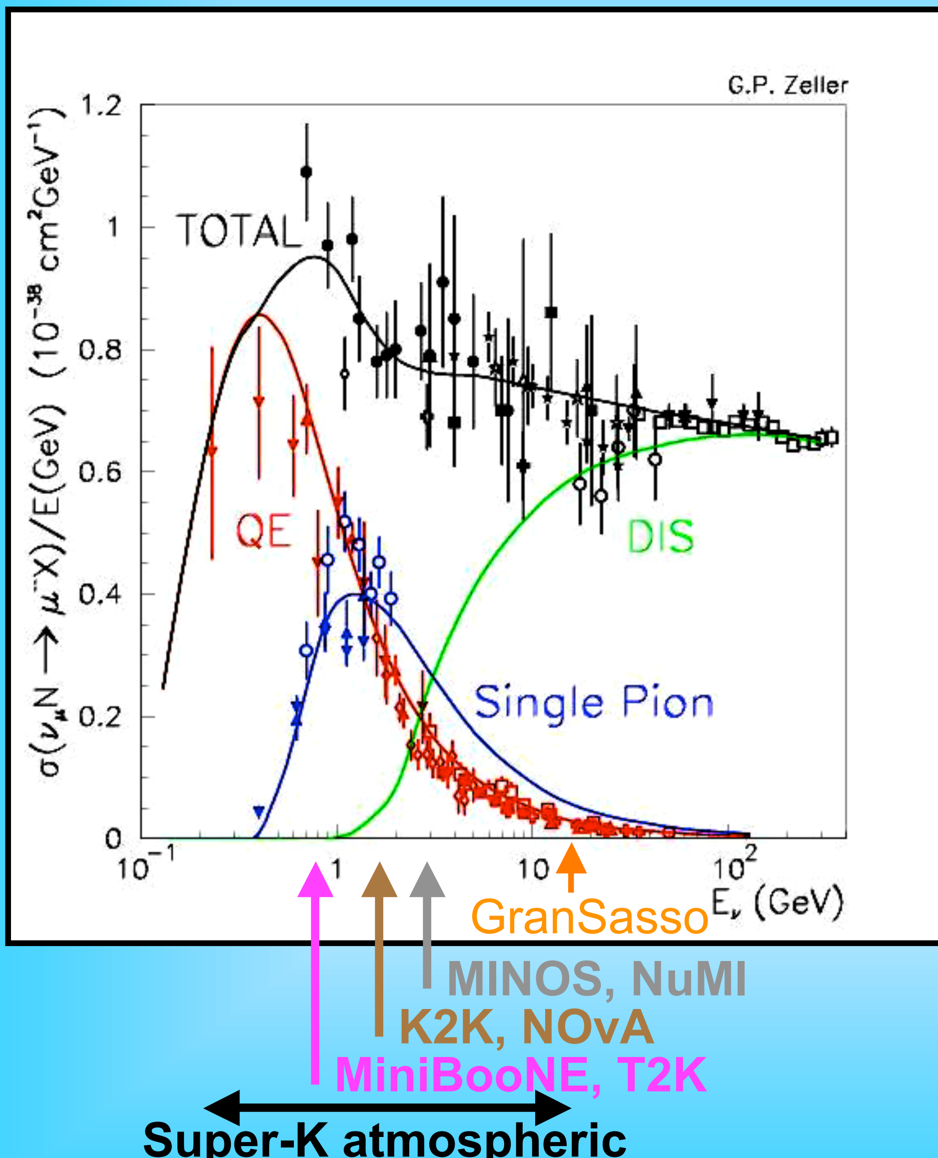
Open Questions in ν Physics

- some big questions that we will be actively trying to answer …

  - what are the masses of neutrinos?
  - what is the mass hierarchy?
  - more precisely measure remaining ν oscillation pars:
    - what are the precise values of Δm^2, θ_{23}
    - is θ_{13} non-zero?
  - is CP violated in the ν sector?

- if want to address these questions, first need to understand how ν's interact with matter … to estimate signal, backgrounds

Neutrino Cross Sections

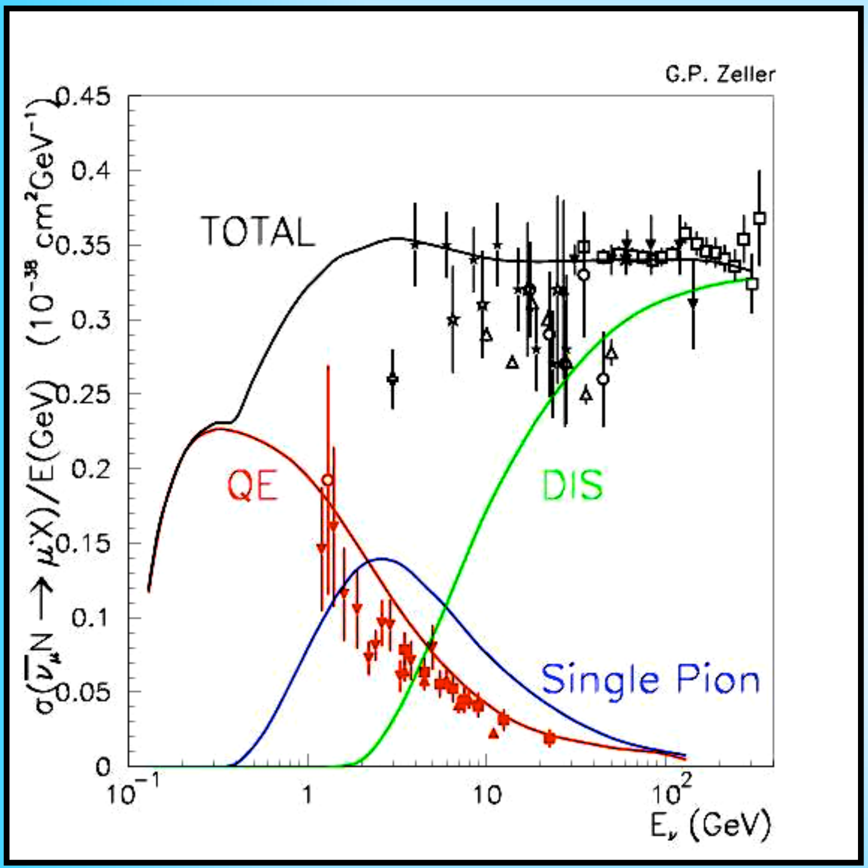


- to see maximum osc effects need to be at “low energy”
- specifically, we care about ν interactions in the range from 100’s-MeV-10’s-GeV

T2K: E_ν ~ 0.7 GeV
NOvA: E_ν ~ 2 GeV
Gran Sasso: E_ν ~ 17 GeV

- will motivate why new ν data is needed (3 regions)

Antineutrino Cross Sections



- need $\overline{\nu}$'s to tell you about mass hierarchy and ~~CP~~
  - will measure ~~CP~~ by comparing oscillation probabilities of $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$
  - need control of $\overline{\nu}/\nu$ ratio to better precision than size of expected asymmetry
  - would prefer not to reply on extrap of model predictions

- so we need to know all of these cross sections for $\overline{\nu}$'s as well

Accelerator-Based ν "Roadmap"

1st σ_ν Measurements

Low E_ν

-showed on previous plot
- low statistics
- 1970's, 1980's

bubble chamber exps

DIS & nucleon structure

High E_ν

- high statistics
- 1980's, 1990's

ν Oscillations

Low E_ν

- more intense ν beams
- new ν data
- revisit σ_ν measurements

K2K, MiniBooNE, MINOS

Dedicated σ_ν Experiments

Low E_ν

- fine-grained detectors
-(bubble chamber-like resolutions)

MINERvA, SciBooNE

Precision ν Oscillations

Low E_ν

- next level of precision

T2K, NOvA, Gran Sasso

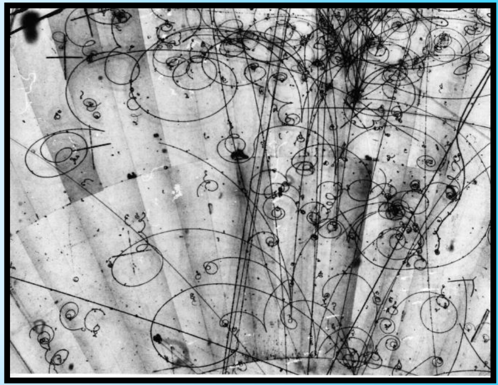
??

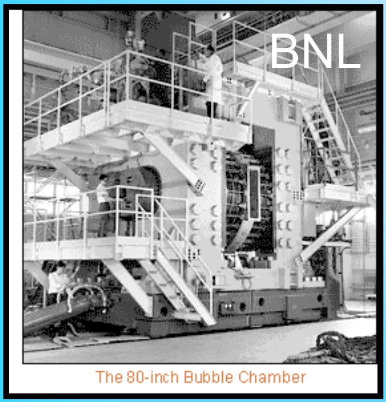
Past ν Cross Section Measurements

• most of present knowledge comes from bubble chamber measurements

- early exps at ANL, BNL, FNAL, CERN, Serpukhov, etc.

- ~20-100% errors due to:
  - low statistics (100's of events)
  - uncertainties in ν flux
    (still have to face today)





- in addition to large errors, results sometimes conflicting (some care in interpreting)

- but despite vintage, very important in constraining MCs
  (in addition to high statistics electron scattering data)

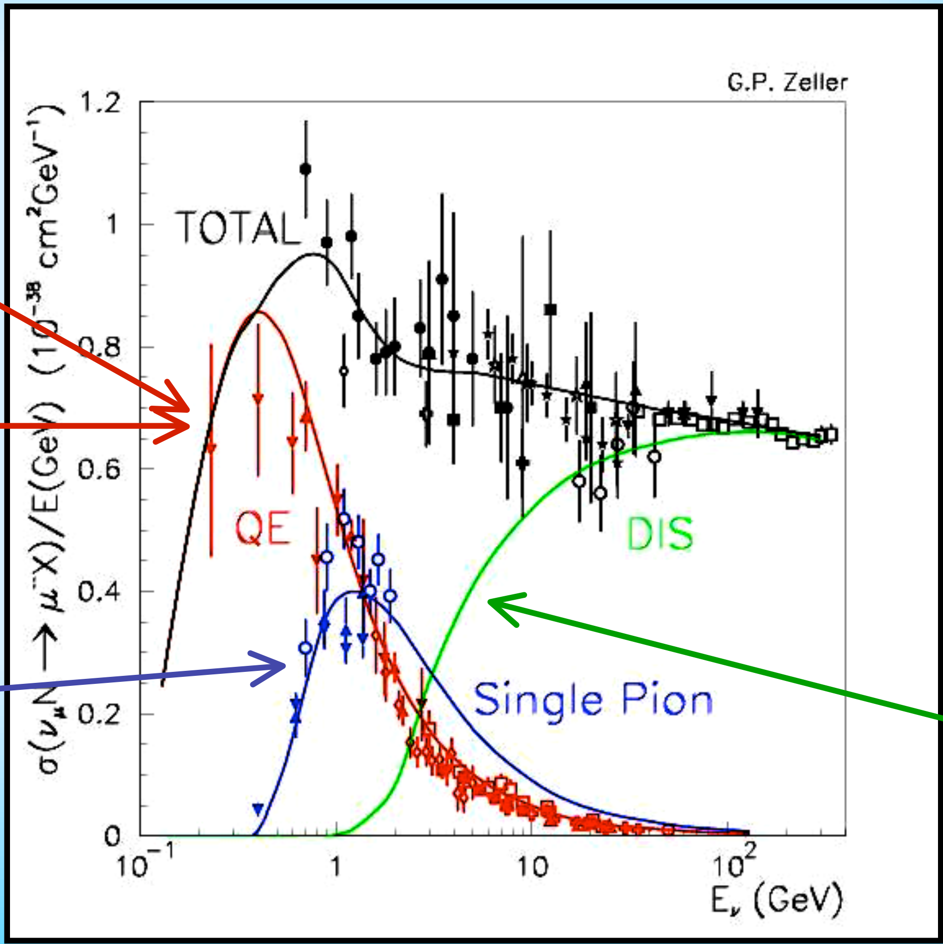
Current Predictions

(notice some of the dates!)

QE scattering
Llewellyn-Smith
(1972)

Fermi gas model
Smith-Moniz
(1972)

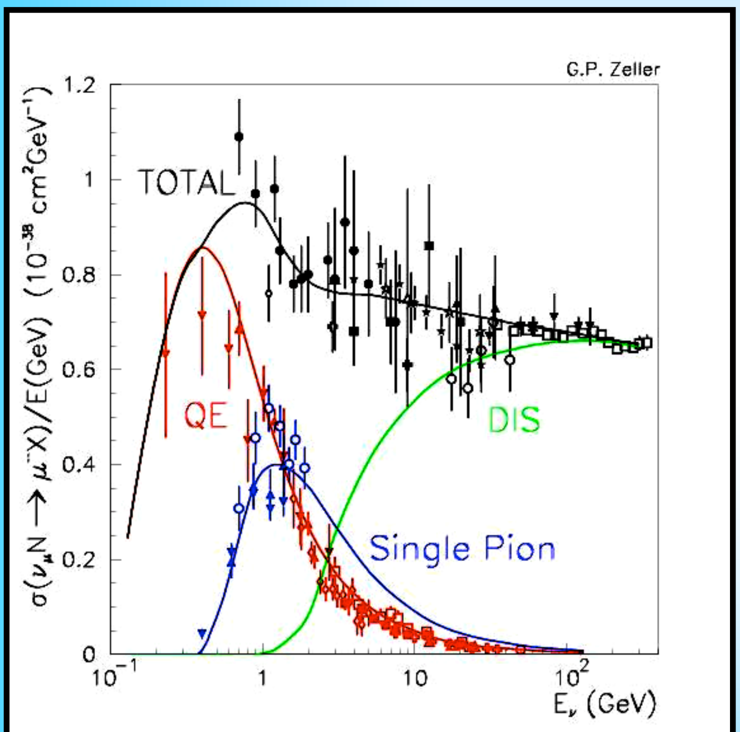
Single π
Production
Rein-Sehgal
(1981,1983)



DIS
Bodek-Yang
(2005)

Status

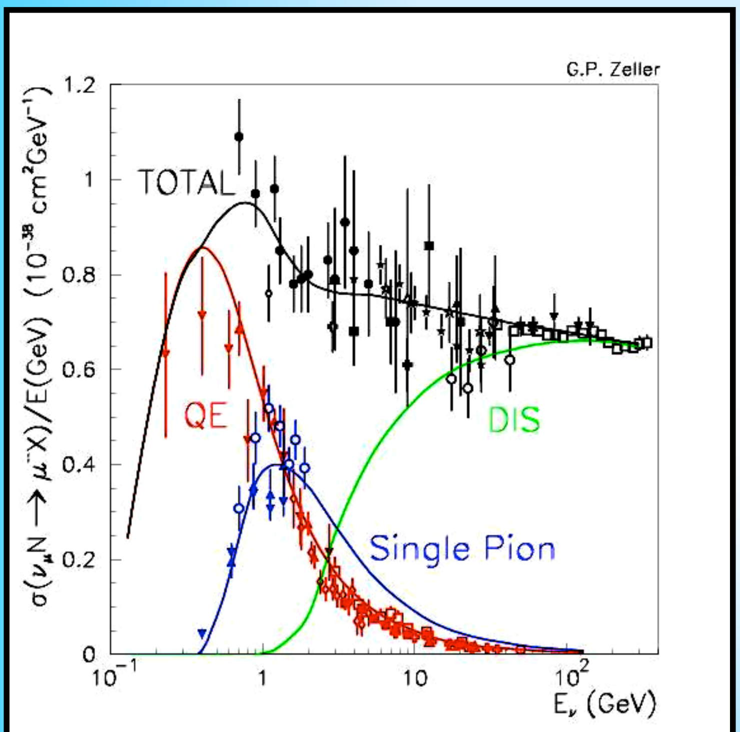
• this is where we've been for a little over 2 decades



• ν interactions have been part of past, but also part of future

Status

- this is where we've been for a little over 2 decades



? =

- ν interactions have been part of past, but also part of future
- in fact, much has happened recently …

New σ_ν Predictions (2006-2007)

- J.A. Caballero *et al.*, nucl-th/0705.1429 (2007)
- K.S. Kim, L.E. Wright, nucl-th/0705.0049 (2007)
- E. Hernandez *et al.*, PL **B647**, 452 (2007)
- C. Giusti *et al.*, nucl-th/0607037 (2006)
- P. Lava *et al.*, PRC **73**, 064605 (2006)
- K.S. Kuzmin *et al.*, Acta Phys. Polon. **B37**, 2337 (2006)
- M.C. Martinez *et al.*, PRC **73**, 024607 (2006)
- N. Jachowicz *et al.*, NP. Proc. Suppl. **155**, 260 (2006)
- M. Valverde *et al.*, PL **B642**, 218 (2006), PL **B638**, 325 (2006)
- A. Butkevich, S. Kulagin, nucl-th/0705.1051 (2007)
- M. Martini *et al.*, Phys. Rev. **C75**, 034604 (2007)
- J.E. Amaro *et al.*, PRC **75**, 034613 (2007)
- O. Benhar *et al.*, nucl-ex/0603029 (2006)
- R. Bradford *et al.*, hep-ex/0602017 (2006)
- J. Nieves *et al.*, Phys. Rev. **C73**, 025504 (2006)
- A. Meucci *et al.*, Acta Phys. Polon, **B27**, 2279 (2006)
- G. Co, ActaPhys.Polon.**B37**, 2235 (2006)

QE

- H. Nakamura *et al.*, hep-ph/0705.3884 (2007)
- E.A. Paschos *et al.*, hep-ph/0704.1991 (2007)
- M. Sajjad *et al.*, NP **A782**, 179 (2007), PRD **75**, 093003 (2007)
- O. Lalakulich, E.A. Paschos *et al.*, Nucl. Proc. Suppl. 159, 133 (2006), PRD **74**,014009 (2006)
- S. Ahmad *et al.*, PRD **74**, 073008 (2006)
- O.Benhar, D. Meloni, PRL **97**, 192301 (2006)
- O. Buss *et al.*, PRC **74**, 044610 (2006), Eur. Phys. J. **A29**, 189 (2006)
- L. Alvarez-Ruso *et al.*, PRC **75**, 055501 (2007)
- E.A. Paschos, A. Kartavtsev, Nucl. Proc. Suppl. **159**, 203 (2006), PRD **74**, 054007 (2006)
- S.K. Singh *et al.*, PRL **96**, 241802 (2006)
- D. Rein, L.M. Sehgal, hep-ph/0606185 (2006)
- B.Z. Kopeliovich, Nucl. Phys. Proc. Suppl. **139**, 219 (2006)

single π production

- S. Kulagin, R. Petti, hep-ph/0703033 (2007)
- O. Lalakulich *et al.*, PRC **75**, 015202 (2007)
- O. Benhar, D. Meloni, hep-ph/0610403 (2006)
- K.S. Kuzmin *et al.*, Phys. Atom. Nucl. **69**, 1857 (2006)
- L. Leitner *et al.*, PRC **73**, 065502 (2006), PRC **74**, 065502 (2006), Int.J.Mod.Phys. **A22**, 416 (2007)

DIS

a lot of theoretical activity!

New Neutrino Data

- new data: order of magnitude higher statistics available now
  - allows us to confront model calculations in new ways

- **present**: new low energy (1-to-10's-of-GeV) ν data from:

results right now

- NOMAD (1995 - 1998)
- K2K (1999 - 2004)
- MiniBooNE (2002 - present)
- MINOS (2005 - present)

coming soon

- **near future**: program of dedicated experiments at FNAL

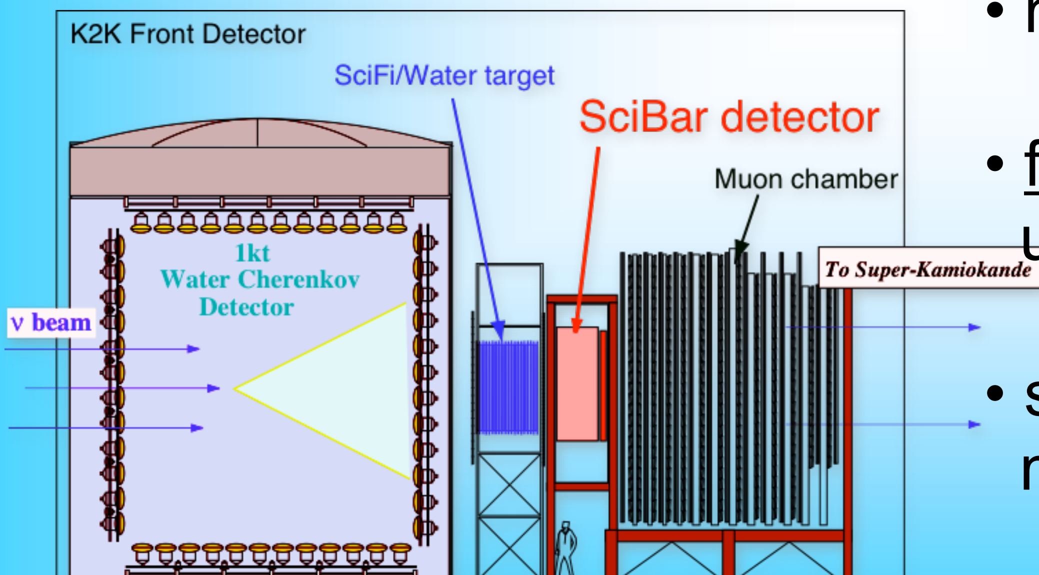
- SciBooNE (2007)
- MINERvA (2009)

- field very active
- cast of characters …

(deserve some intro)

K2K

- designed to confirm atm ν oscillations (Super-K)
- KEK, 12 GeV protons
  - $\langle E_\nu \rangle$ = 1.3 GeV



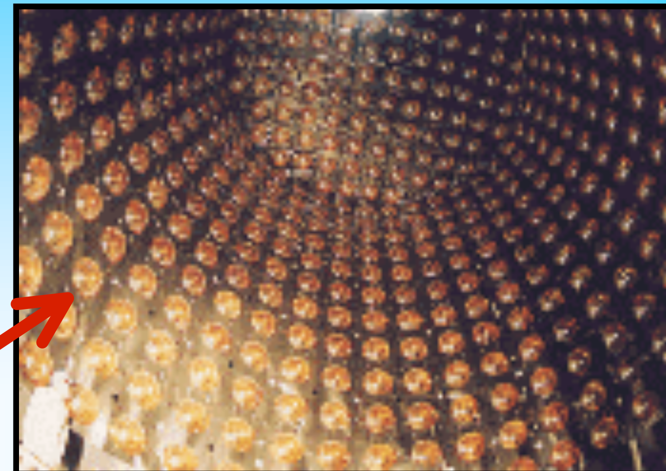
- not only first LBL exp …
- first on our list to provide updated low E σ_ν meas
- suite of near detectors measure un-oscillated ν

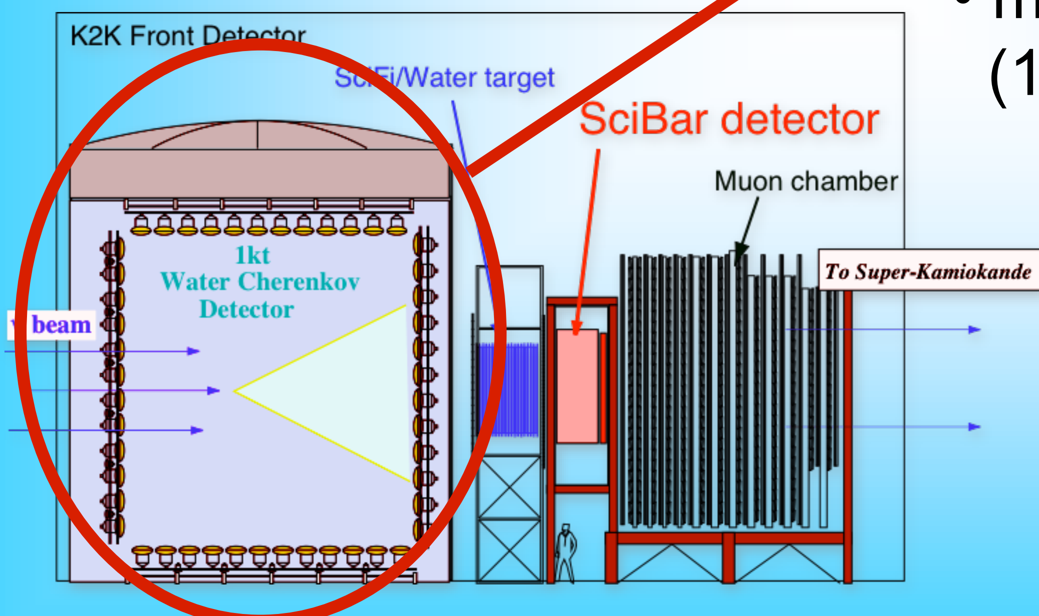
K2K

- 1kton water Cerenkov detector

- SciFi (water target)

- SciBar (carbon target)



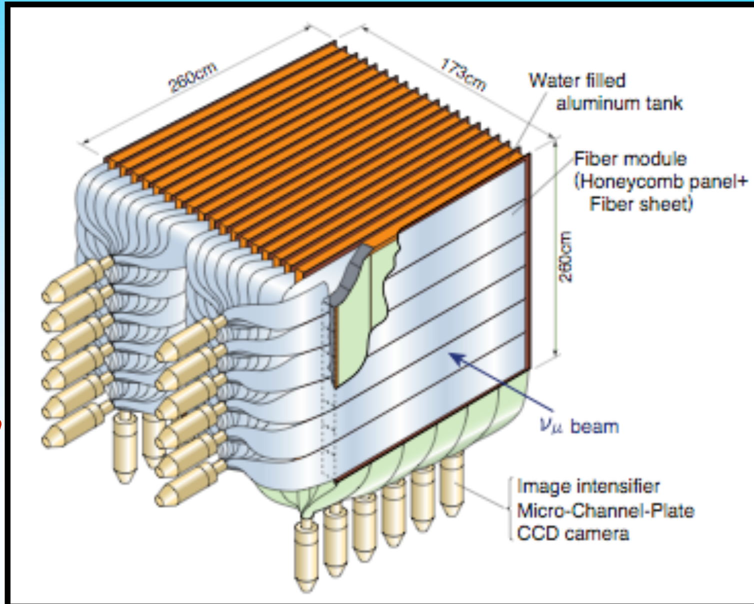


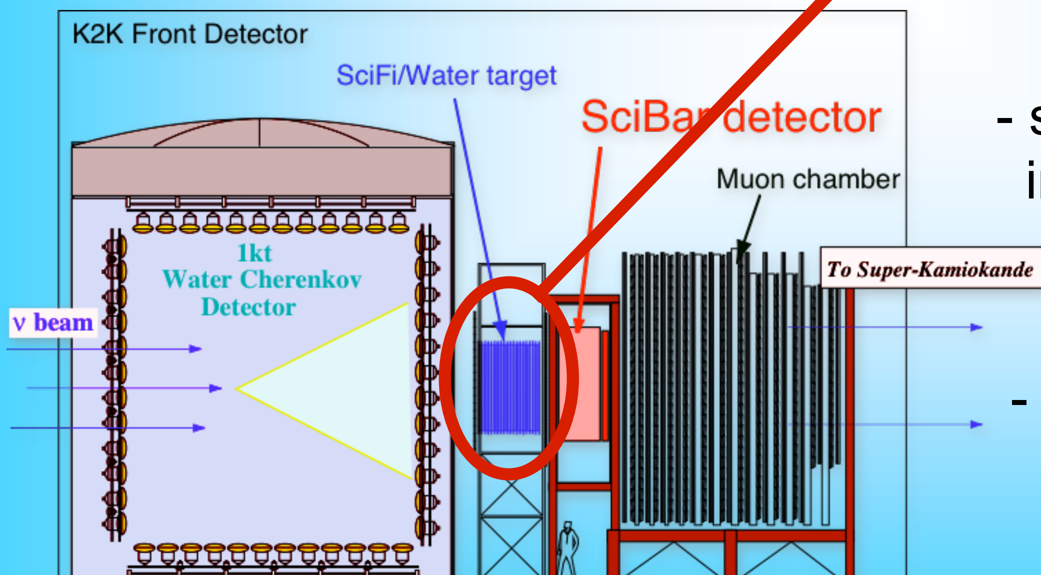
- miniature replica of Super-K ($1/50^{th}$ scale)

  - PMTs arranged on inner wall detect Cerenkov light

K2K

- 1kton water Cerenkov detector
- SciFi (water target)
- SciBar (carbon target)



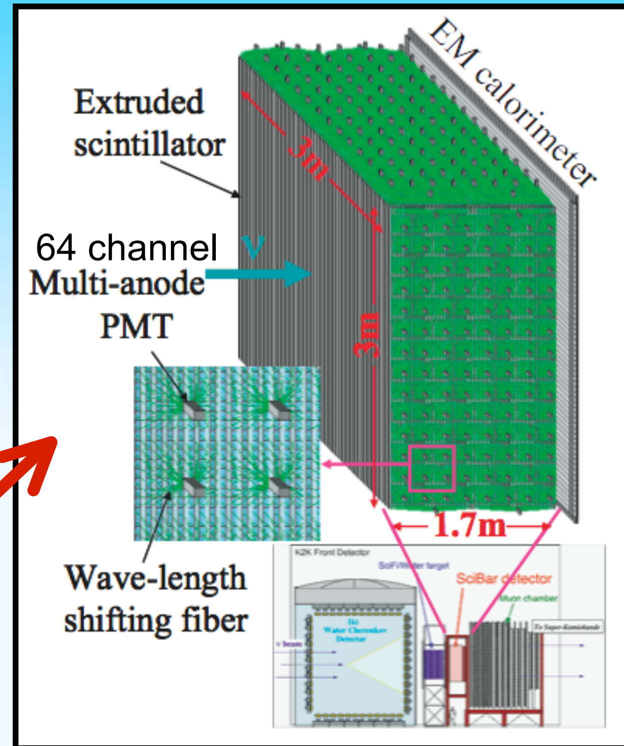


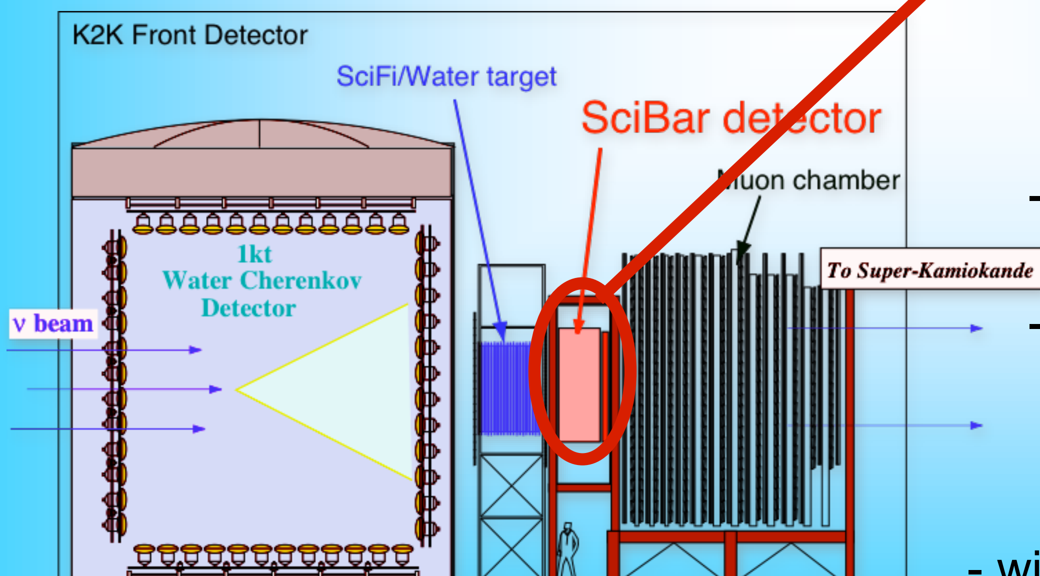
- scintillating fiber tracker (SciFi) in between H_20 tanks

- unlike 1kton, every particle is above Cerenkov threshold, so can see everything

K2K

- 1kton water Cerenkov detector
- SciFi (water target)
- SciBar (carbon target)





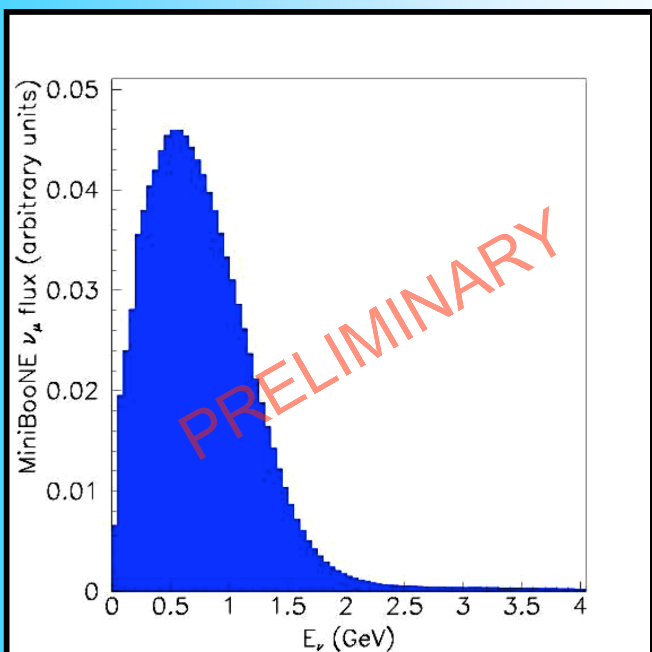
- installed later (2003)

- >14k scintillator strips read out by WLS fibers (same as MINOS scintillator)

- will be showing results from all 3

MiniBooNE

- single detector, designed to check LSND
- FNAL Booster, 8 GeV protons
  - $\langle E_\nu \rangle$ = 0.8 GeV

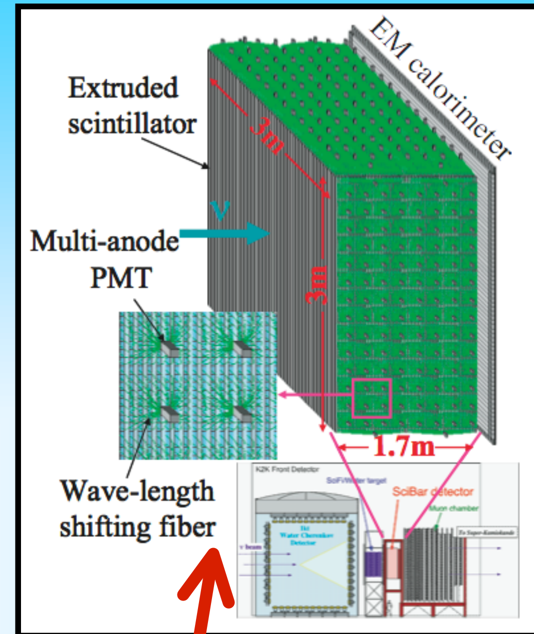


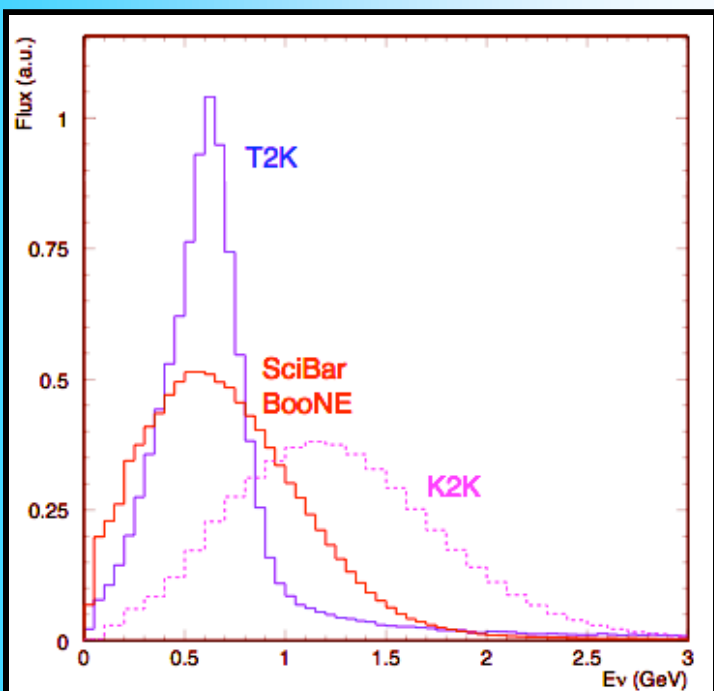
- Cerenkov detector (CH_2)
  - 1M ν and $\bar{\nu}$ events
  - record size samples in this energy range

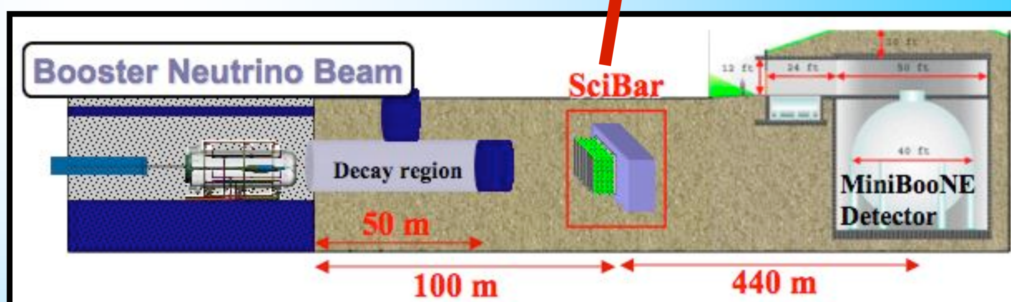
will also be showing preliminary look at new antineutrino data

SciBooNE

- dedicated ν cross section experiment
- FNAL Booster, 8 GeV protons
  - $\langle E_\nu \rangle = 0.8$ GeV
- fine-grained SciBar shipped to FNAL







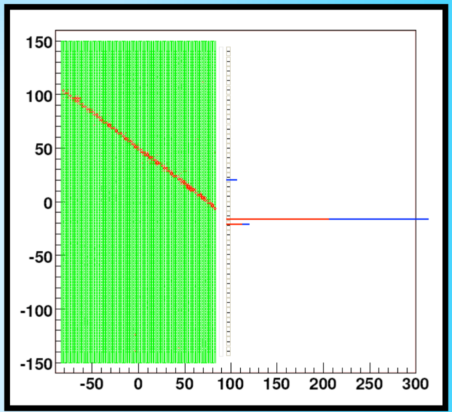
- couples well-known beam, detector
- has come a long way in a short time

(experiment 1st proposed in Nov 2005)

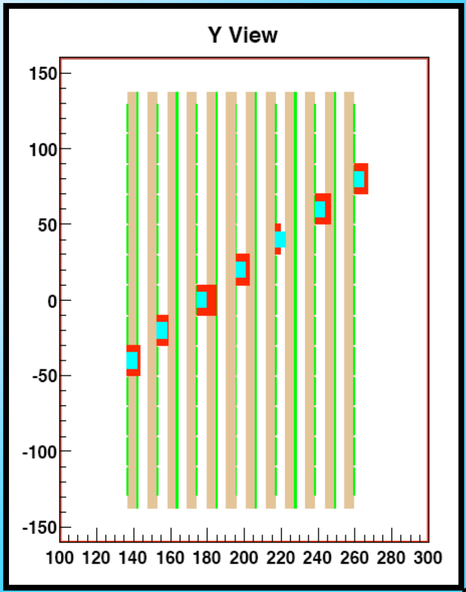
SciBooNE Developments

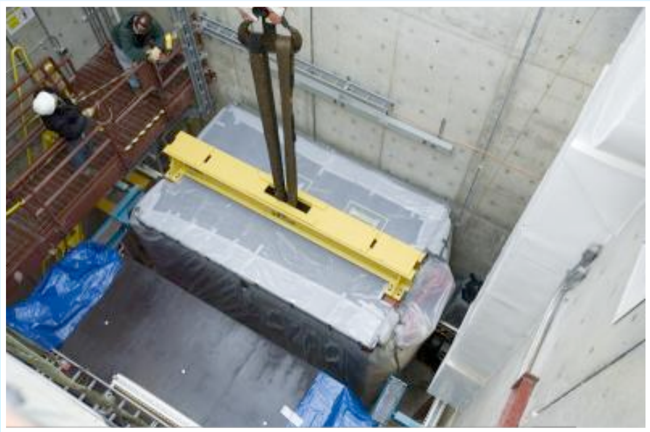
- March: 1st comic rays in SciBar and MRD
- April: detectors move to enclosure

SciBar/EC



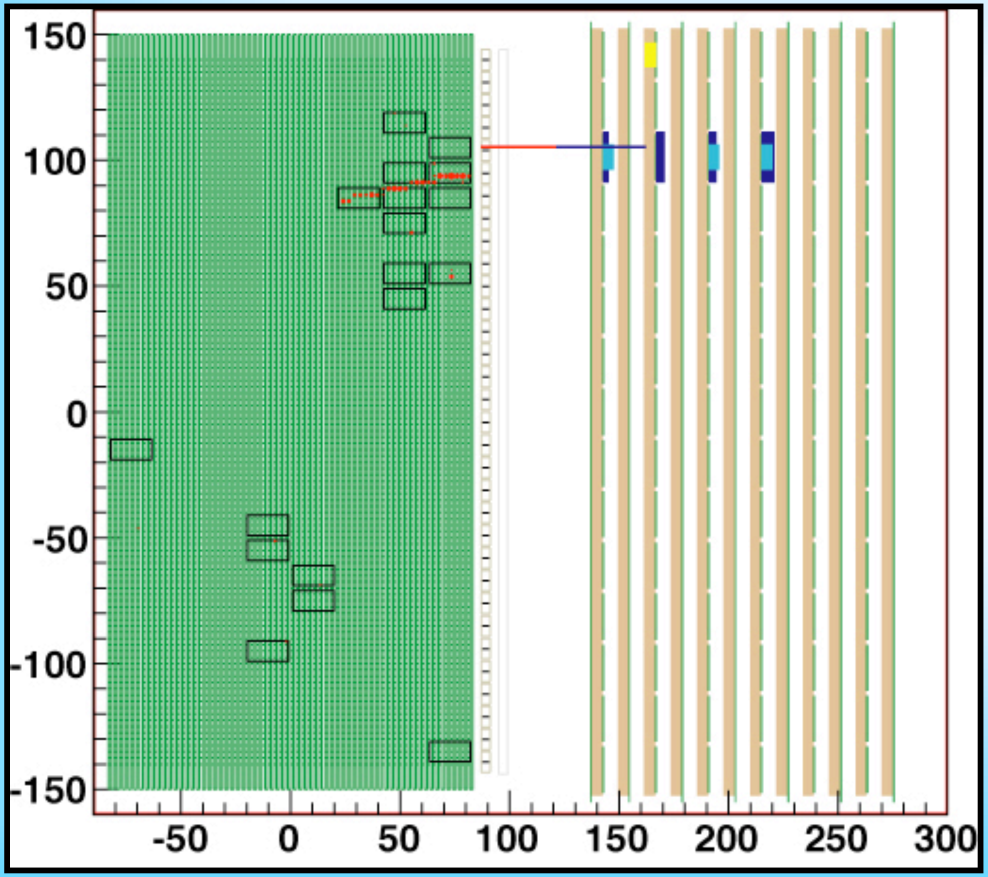
MRD





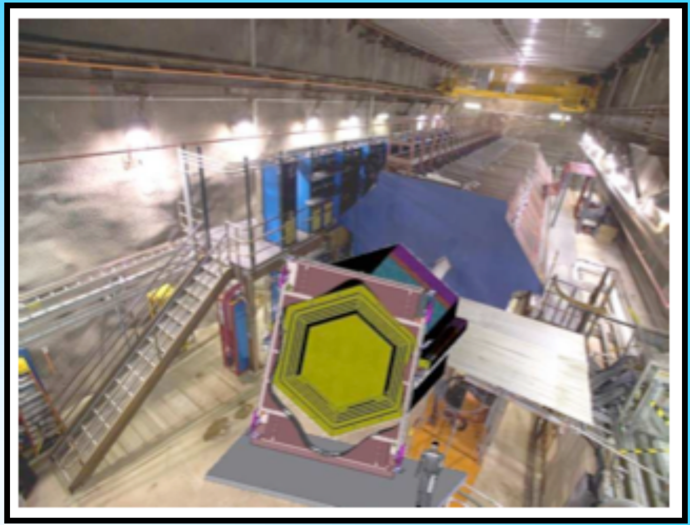
SciBooNE Developments

- exciting news: 1st ν's observed two days ago (May 30th)



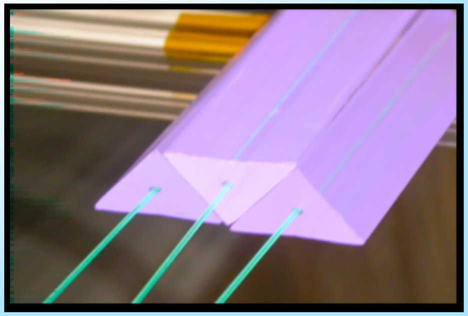
(R. Napora, NuInt07)

MINERνA



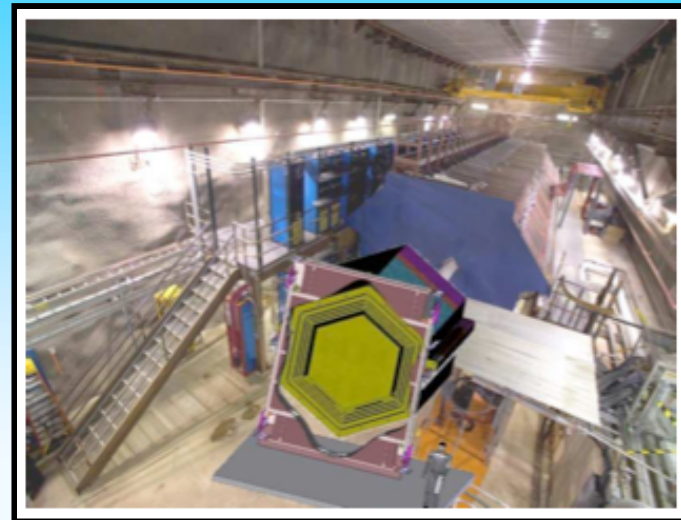
- dedicated ν cross section experiment
- FNAL MI,120 GeV protons
- fully active detector will sit directly upstream of MINOS

- solid scintillator strip detector surrounded by sampling detectors



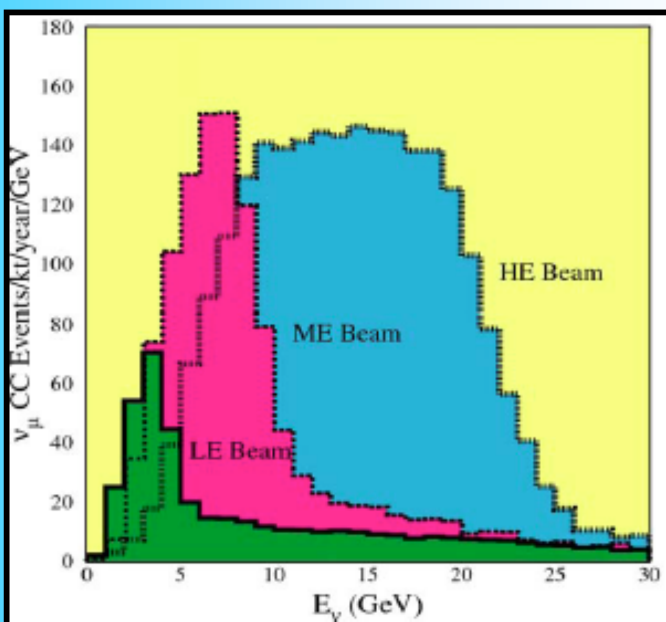
- extruded triangular scintillator strips embedded w/ WLS fibers (similar to SciBar, MINOS)

MINERvA



- dedicated ν cross section experiment
- FNAL MI,120 GeV protons
  - LE: E_ν^{peak} = 3 GeV
  - ME: E_ν^{peak} = 7 GeV
  - HE: E_ν^{peak} = 12 GeV

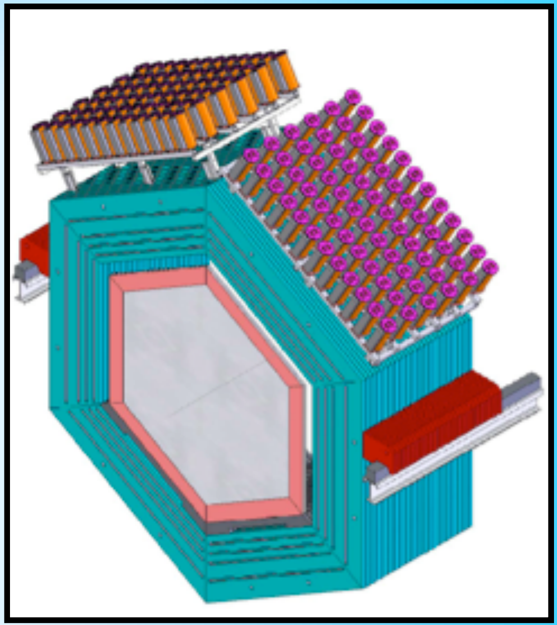
(fluxes for different target positions)



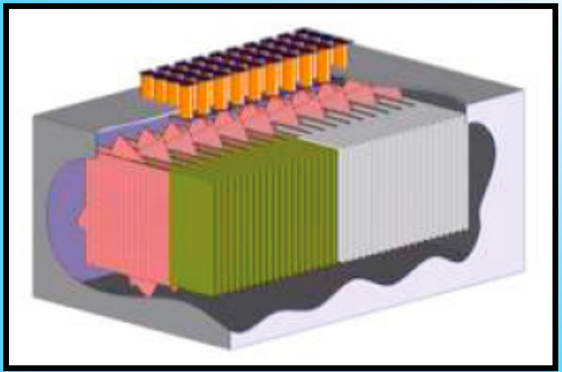
- observe ν ints over broad E range
- impressive physics program:
  - all channels from QE to DIS
- nuclear targets (He, C, Fe, Pb)
  - allow detailed study of nuclear effects in ν's for the first time
- diverse collaboration (HEP, NP, e^-)

MINERvA Developments

- March: granted CD1/2/3a approval
- already built full module prototype
  (test mechanical structure, source tested for uniformity)



- next year: multi-plane tracking prototype
  - ~20 of these modules
  - start taking data w/ prototype next year



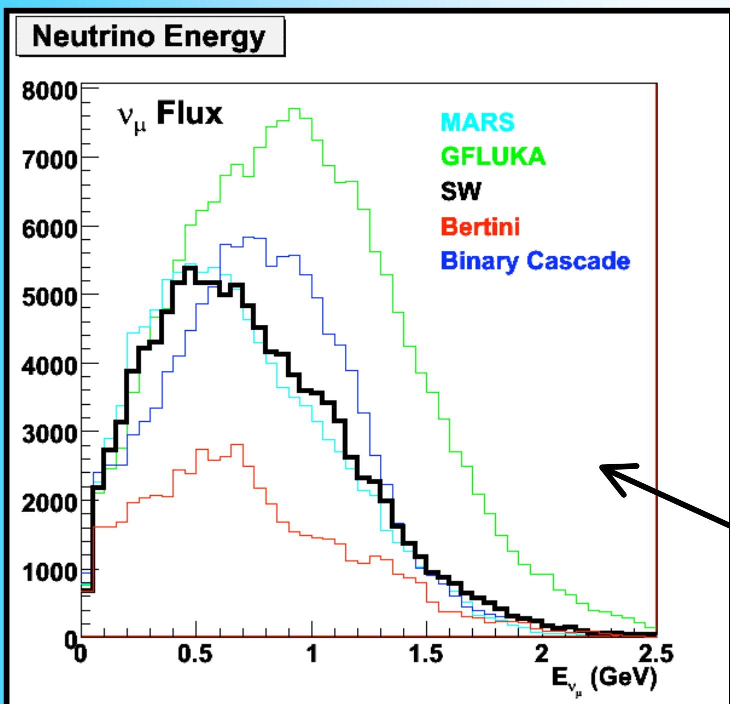
- coupled w/ test beam program planned
  - next Fall
  - MINERvA TB detector in M-Test

- ν data in 2009!

Modern Challenges

(1) predicting incoming neutrino flux

- situation has been greatly improving but still true that …



- how well know ν flux sets limit on how well can meas absolute σ_ν

$$N_\nu = \sigma_\nu \times \varepsilon_{det} \times \Phi_\nu$$

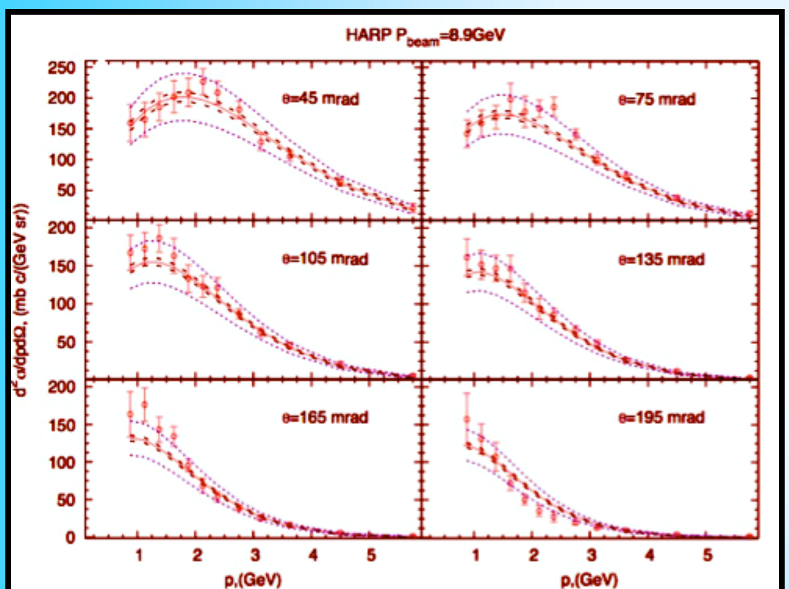
in the spirit of a historical review …
example: 8 GeV p scattering off Be
shows resulting ν_μ fluxes at 550 m

demonstrates level of uncertainty
in not-so-distant past

Modern Challenges

(1) predicting incoming neutrino flux

- situation has been greatly improving but still true that …



ex: new HARP measurement (hep-ex/0702024)

- how well know ν flux sets limit on how well can meas absolute σ_ν

$$N_\nu = \sigma_\nu \times \varepsilon_{det} \times \Phi_\nu$$

- meson production data is crucial (HARP, MIPP, E910, SPY, NA49)

- modern goal: 5-10%

(2) in an energy range where nuclear effects are important

Nuclear Effects

- modern ν osc exps measure ν interactions on nuclear targets (O, C, Fe, Ar, Pb, …) - need to understand ν ints on nuclei

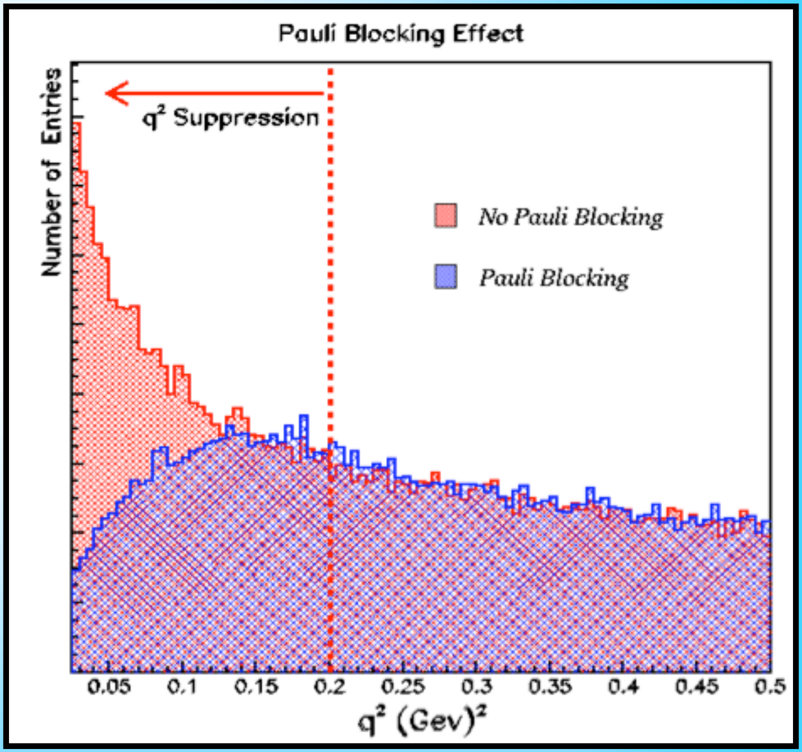
(1) ν interaction w/ bound nucleon

simplest & most common approach
Is to use Fermi gas model:

- Pauli blocking
- Fermi motion

will come back to this topic later

(F. Sanchez, K2K)



(nuclear effects largest at low E_ν, low Q^2)

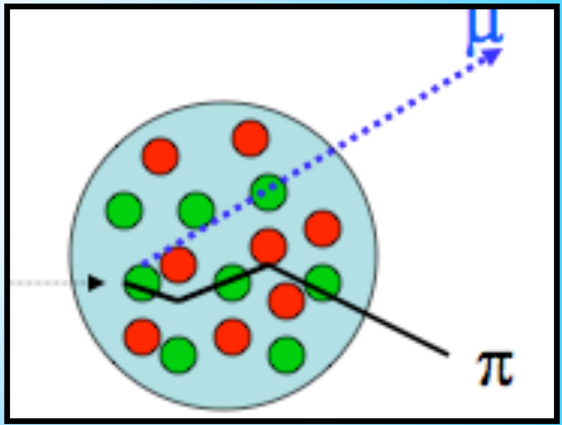
Nuclear Effects

- modern ν osc exps measure ν interactions on nuclear targets (O, C, Fe, Ar, Pb, …) - need to understand ν ints on nuclei

(2) propagation of final state hadrons in nucleus
("final state interactions")

- pions and nucleons can rescatter

(can change momentum, direction, identity as travel through nucleus)



- calculate probabilities of all these processes w/ MC methods

Nuclear Effects

low energy is tough, but necessary that we understand

(1) ν interaction with bound nucleon

(2) propagation of hadrons in nucleus

- impact kinematics, rates, and observed final states

- studied extensively in e, μ DIS, but only glanced at over limited kinematic range in early, low stat ν experiments

  - GGM, SKAT (propane-freon)
  - CHARM, CHARMII (marble, glass)
  - Serpukov (Al)
  - FNAL (Ne)

- this situation will soon change (MINERvA!) - will point out examples

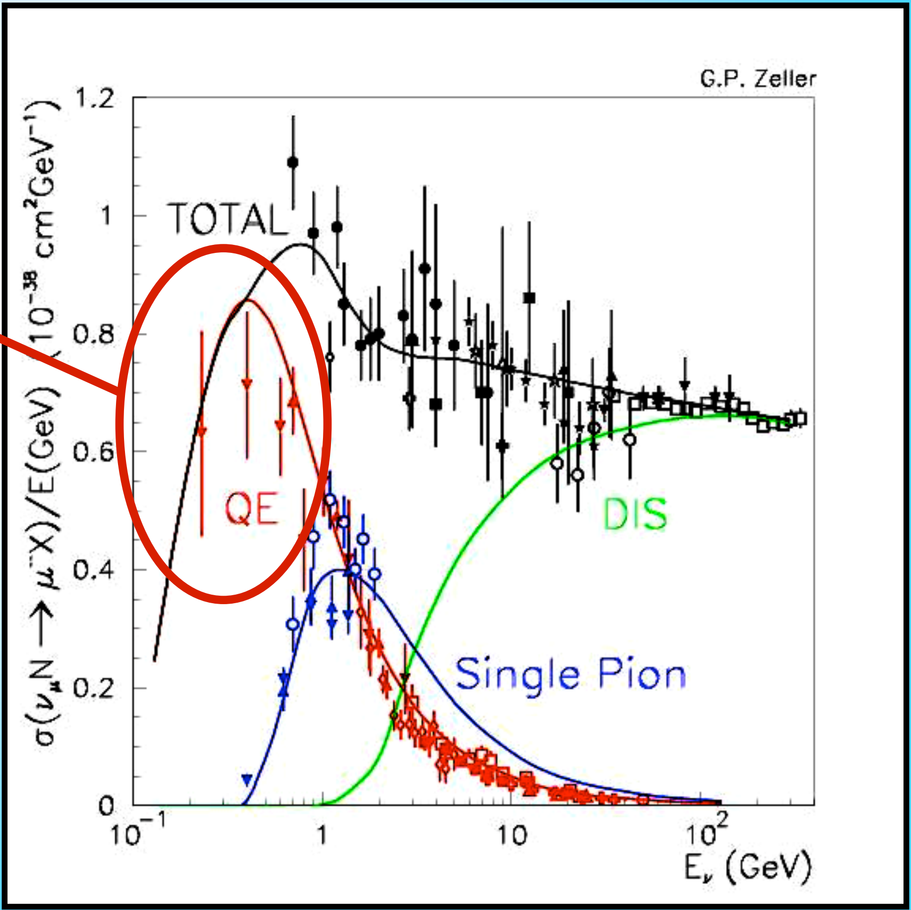
Low Energy ν Interactions in Nuclei

- let's get to some physics results … structure of rest of talk:

(1) quasi-elastic (QE)
- dominates $E_\nu \lesssim 1$ GeV

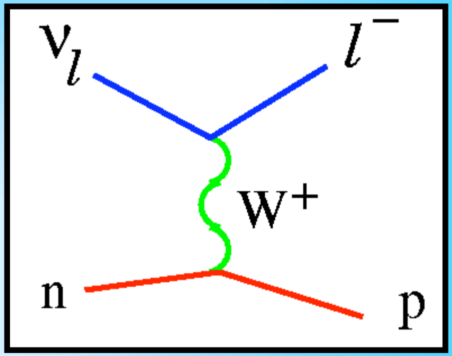
(2) NC, CC 1π production

(3) CC inclusive, DIS
- dominates $E_\nu \gtrsim 5$ GeV

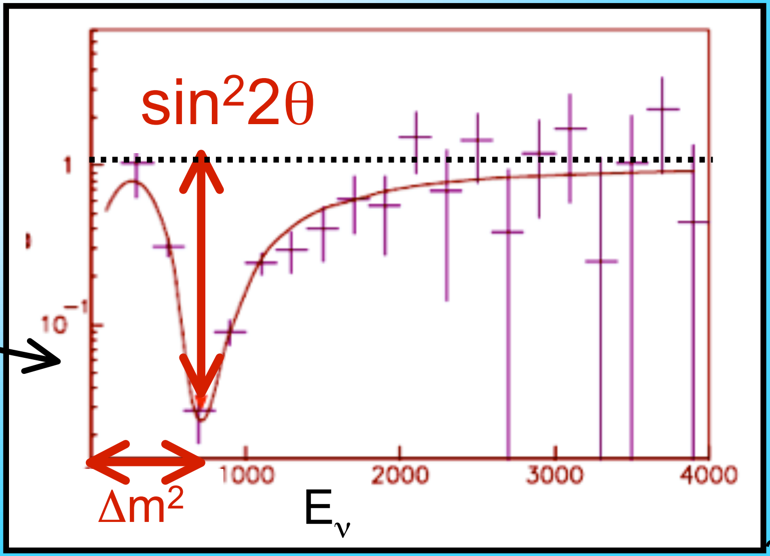


Quasi-Elastic (QE) Scattering

Why important?

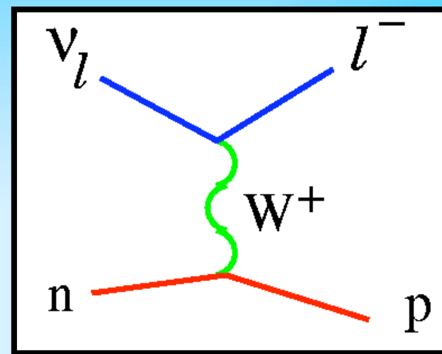


- **important for ν oscillation experiments** $\nu_\mu\, n \rightarrow \mu^-\, p$
  - 2-body so can reconstruct E_ν, tag flavor of incoming ν
  - also dominant interaction ~1 GeV, so forms signal samples …
  - ν_e **appearance**: ν_e QE main signature
  - ν_μ**disappearance**: need $\sigma_{QE}(E_\nu)$ since will be looking for distortions in shape of survival probability as a function of energy



(C. Walter, T2K)

Quasi-Elastic (QE) Scattering



Why important?

- **important for ν oscillation experiments** $\nu_\mu\, n \rightarrow \mu^-\, p$
  - 2-body so can reconstruct E_ν, tag flavor of incoming ν
  - also dominant interaction ~1 GeV, so forms signal samples …
- **interesting in their own right**
  - valuable probe of structure of nucleon
  - extract info on axial-vector form factor of the nucleon (in a way that is difficult to obtain in e^- scattering, will show new measurements!)

To Set the Scale: Past QE Data

$< E_\nu >$	Exp	Mode	Target	Year	# QE events
0.7 GeV	ANL	ν	D_2	1973	166
0.5 GeV	ANL	ν	D_2	1977	600
2 GeV	CERN	ν	C_3H_8	1979	26
2 GeV	GGM	ν	C_3H_8	1979	622
0.5 GeV	ANL	ν	D_2	1981	1737
1.6 GeV	BNL	ν	D_2	1981	1138
5-200 GeV	FNAL	ν	D_2	1983	362
6-7 GeV	SKAT	ν	CF_3Br	1988	464
9 GeV	SKAT	ν	CF_3Br	1990	540
54 GeV	BEBC	ν	D_2	1990	552
1.6 GeV	FNAL	ν	D_2	1990	2538
5-7 GeV	SKAT	ν	CF_3Br	1992	1465
2 GeV	GGM	$\bar{\nu}$	$C_3H_8CF_3Br$	1979	766
1.3 GeV	BNL	$\bar{\nu}$	H_2	1980	13
16 GeV	FNAL	$\bar{\nu}$	NeH_2	1984	405
6-7 GeV	SKAT	$\bar{\nu}$	CF_3Br	1988	52
1.2 GeV	BNL	$\bar{\nu}$	CH_2	1988	2919
9 GeV	SKAT	$\bar{\nu}$	CF_3Br	1990	159
5-7 GeV	SKAT	$\bar{\nu}$	CF_3Br	1992	256

- multiple exps have made QE measurements
  (but stopped as moved on to other things)

neutrino
($\nu_\mu\, n \rightarrow \mu^-\, p$)
~10,000 events total

antineutrino
($\bar{\nu}_\mu\, p \rightarrow \mu^+\, n$)
~4,600 events total

QE Cross Section Measurements

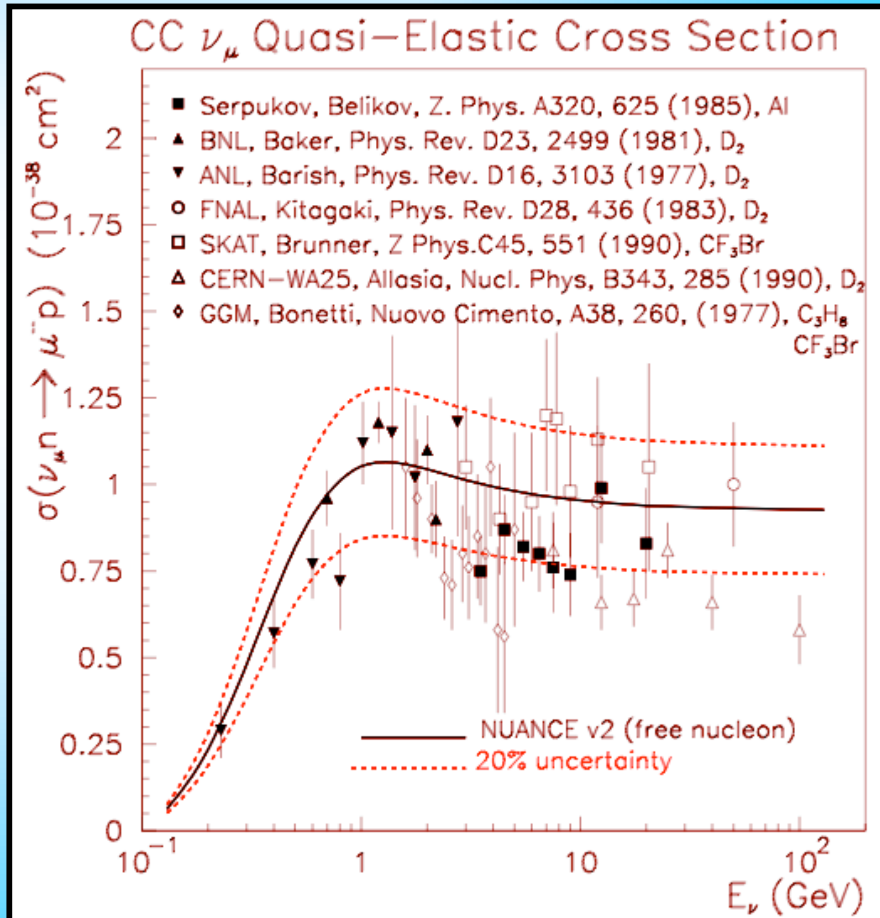
- this data establishes what we know about the QE σ

$$\nu_\mu\, n \rightarrow \mu^-\, p$$

- ~15-20% uncertainty
  (considerable spread for any given E_ν)

- less well-known in threshold region important for osc exps

- low E data mostly on D_2
  (preferred for their simplicity, but not really relevant for meas want to make now)



QE Cross Section Prediction

- QE cross section can be written in terms of nucleon FFs:

C.H. Llewellyn Smith, Phys. Rep. 3C, 261 (1972)

$$< N'|J_\mu|N > \; = \; \overline{u}(N') \left[\gamma_\mu F_V^1(q^2) + \frac{i\sigma_{\mu\nu} q^\nu \xi F_V^2(q^2)}{2M} + \gamma_5 \gamma_\mu F_A(q^2) \right] u(N)$$

- form factors describe underlying nucleon structure

  (and come from two sources)

QE Cross Section Prediction

- QE cross section can be written in terms of nucleon FFs:

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$$< N'|J_\mu|N > \; = \; \overline{u}(N')\left[\gamma_\mu F_V^1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu \xi F_V^2(q^2)}{2M} + \gamma_5\gamma_\mu F_A(q^2)\right] u(N)$$

- $F_v(Q^2)$: **vector** form factor well-determined (electron scattering)

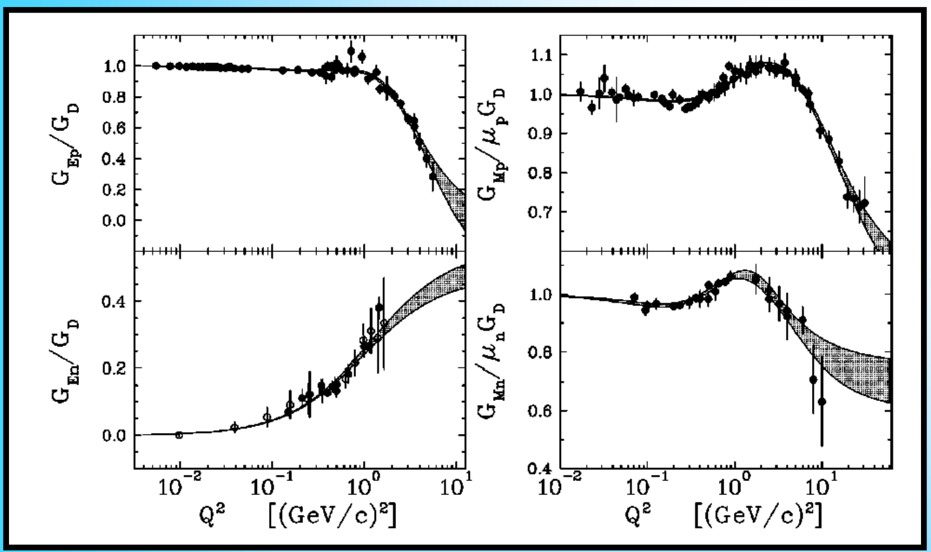
$$F_v\,(Q^2) \sim \frac{1}{(1+Q^2/M_v{}^2)^2}$$

- historically, vector form factor assumed to have dipole form
- F_v in ν related to $G^{n,p}_{E,M}$ in e^-

Vector Form Factors

- from electron scattering, we now know vector form factor is not really dipole

- see some of the largest deviations at high Q^2
  (high Q^2 has been an evolving story in electron sector, will get back to)



J.J. Kelly, PRC**70**, 068202 (2004)

plus updated fits soon from "BBBA2005" (hep-ex/0602017)
Bradford, Bodek, Budd, Arrington
and a new publication

- this provides vector portion of QE σ used in ν simulations

QE Cross Section Prediction

- QE cross section can be written in terms of nucleon FFs:

C.H. Llewellyn Smith, Phys. Rep. 3C, 261 (1972)

$$< N'|J_\mu|N > \;=\; \overline{u}(N')\left[\gamma_\mu F_V^1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu \xi F_V^2(q^2)}{2M} + \gamma_5\gamma_\mu F_A(q^2)\right]u(N)$$

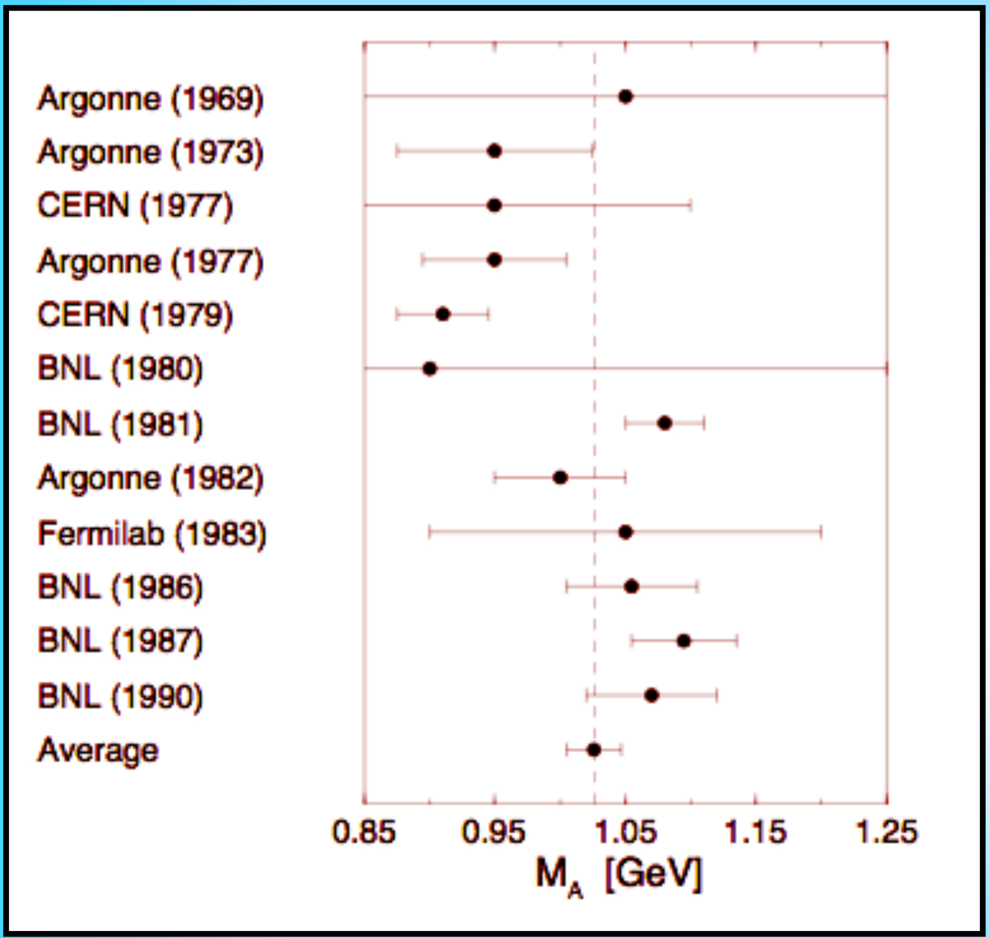
- $F_A(Q^2)$: **axial-vector** form factor less well known (ν scattering)

$$\boxed{F_A(Q^2) \;=\; \frac{g_A}{(1+Q^2/M_A^2)^2}}$$

function of a single parameter: **"axial mass"**

- \+ nuclear effects (most ν exps use relativistic Fermi Gas model)

Past Determinations of M_A



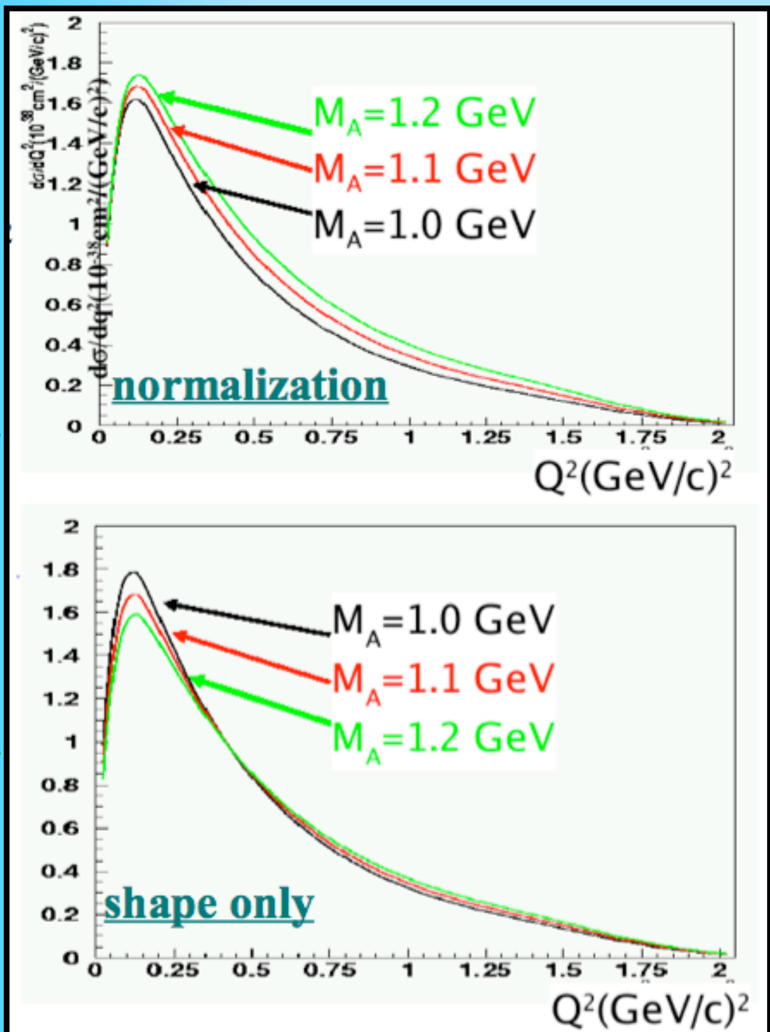
world avg: M_A = 1.03 ± 0.02 GeV
J.Phys.**G28**, R1 (2002)

- this parameter must be determined experimentally
- collection of past ν data:

  M_A=1.03 GeV

- so, have been using world average largely set by D_2 in our ν simulations
- a lot of interest in this & attempts to remeasure

How Do You Measure M_A?



(R. Gran, Nu06)

- varying M_A has two effects:

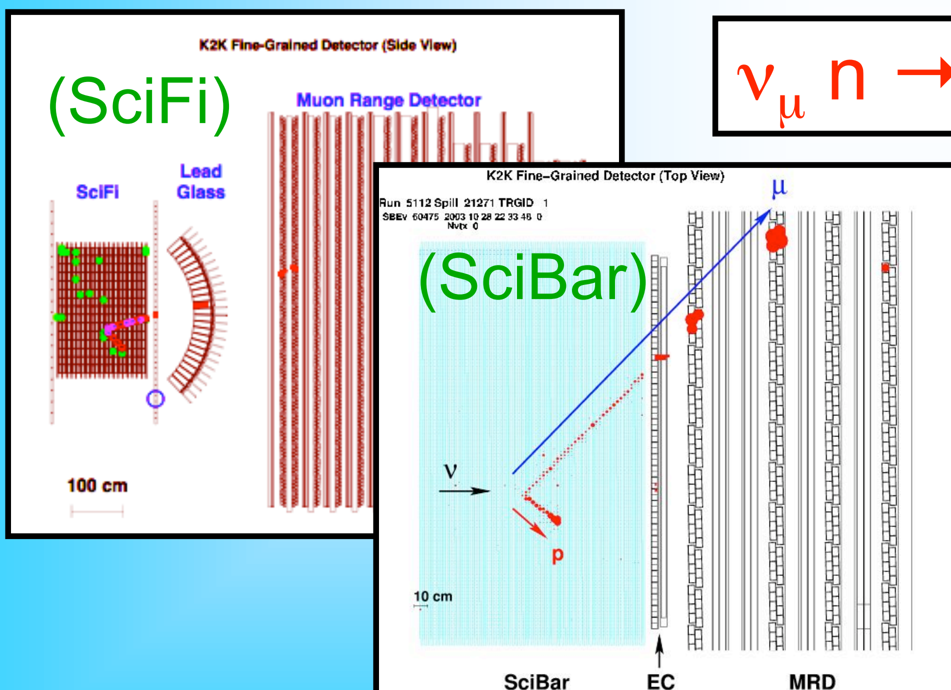
(1) **changes total σ**
($\uparrow M_A$, $\uparrow \sigma$)

(2) **changes Q^2 dependence**
($\uparrow M_A \rightarrow$ harder Q^2)

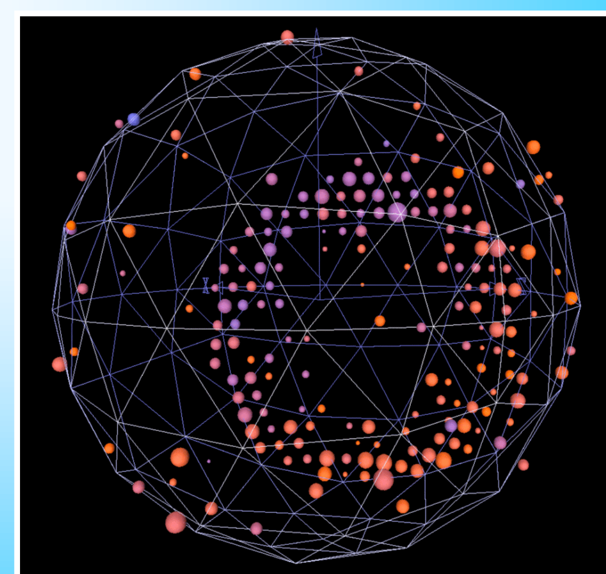
- typically ν experiments measure M_A using 2nd method
(many past experiments did both)

Modern M_A Analyses

K2K	MiniBooNE
+ fine-grained detection reconstruct energy & direction of outgoing proton	+ statistics (order magnitude more QE events than has been previously available at low E)



$\nu_\mu n \to \mu^- p$



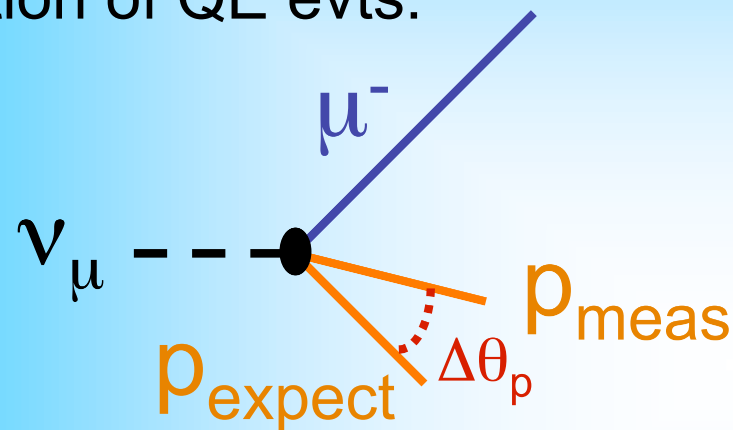
(single ring topology)

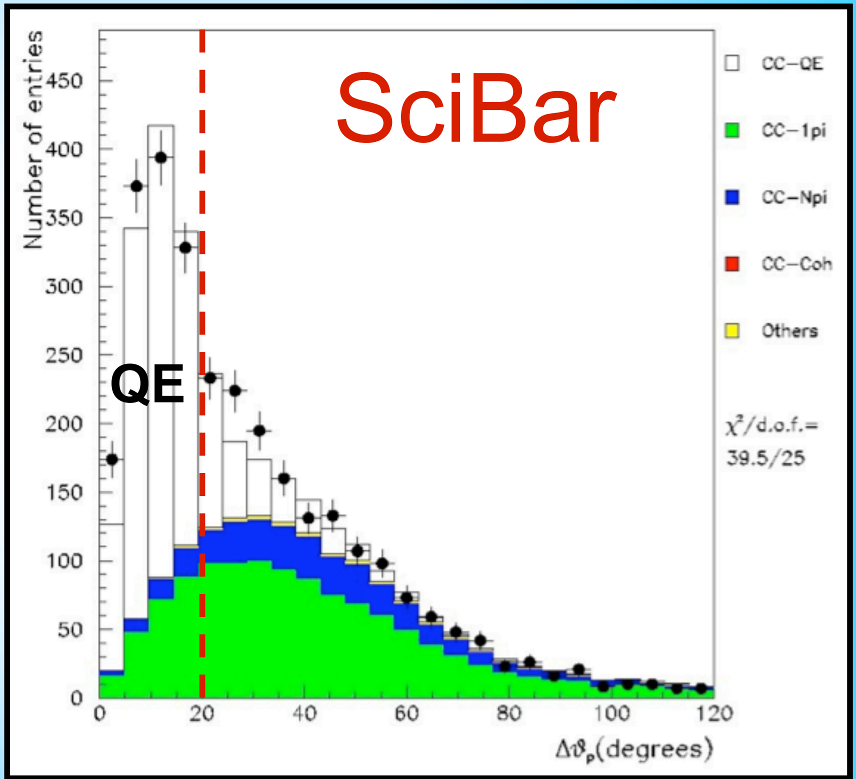
Two Different Approaches

K2K	MiniBooNE
fine-grained detectors (H_2O SciFi, ^{12}C SciBar)	Cerenkov detector (^{12}C)
fit three CC ν_μ samples: -1-track : 8555 events - 2-track QE: 2187 events - 2-track non-QE: 2190 events	fit single ν_μ QE sample - 193,709 events
max likelihood fit to Q^2 & E_ν - M_A, norm, $\Phi(E_\nu)$, non-QE/QE, 2-track/1-track, p re-scattering	least-squares fit to Q^2 - M_A, Pauli-blocking par
$Q^2 > 0.2\ GeV^2$	$0 < Q^2 < 1\ GeV^2$
reconstruct proton	tag muon-only

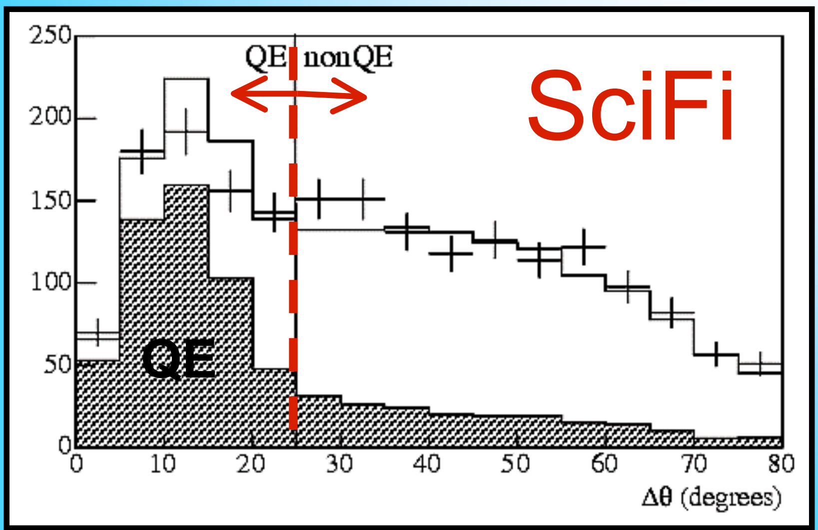
K2K QE Selection

• once 2-track events, kinematic info can be used to enhance fraction of QE evts:





(F. Sanchez, NuInt07)



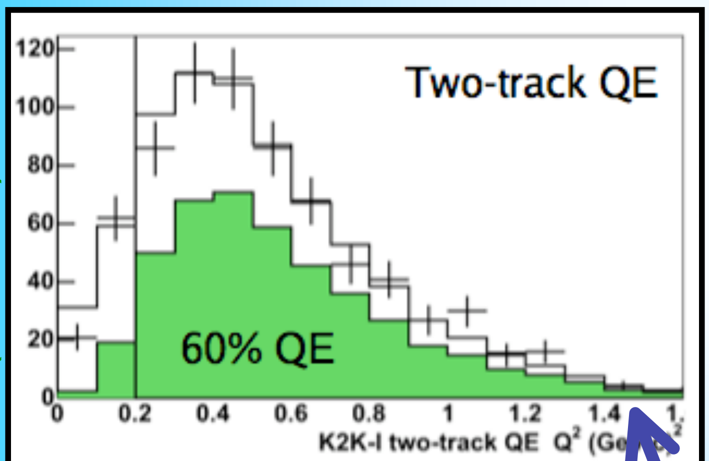
(R. Gran *et al.*,PRD**74**, 052002 (2006))

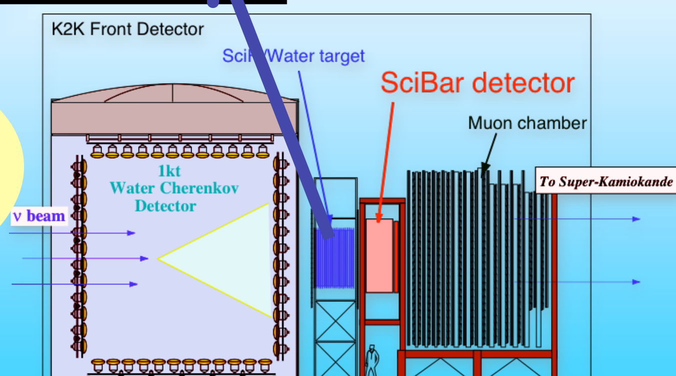
K2K M_A Fit Results

SciFi, H_2O (Q^2>0.2):

- M_A = 1.20 ± 0.12 GeV
- χ^2/df = 261/235

(R. Gran)





1st determination of M_A on a water target!

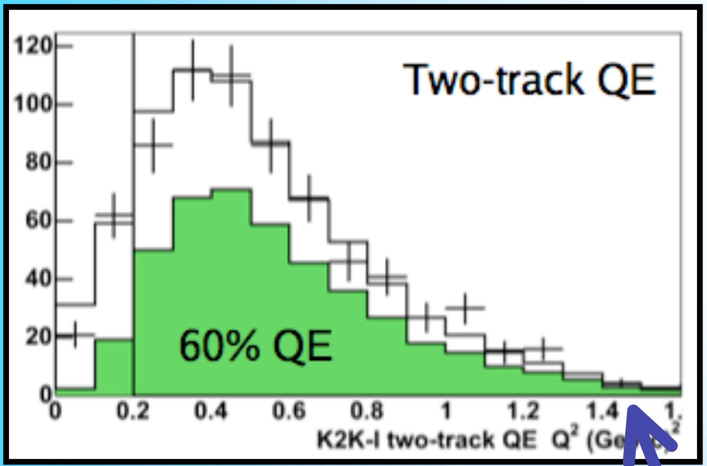
K2K M_A Fit Results

NEW!

SciFi, H_2O (Q^2>0.2):

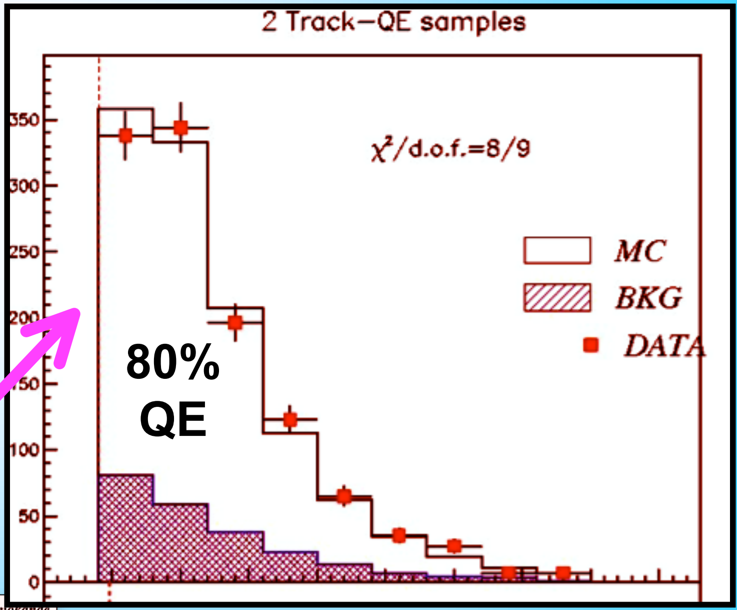
- M_A = 1.20 ± 0.12 GeV
- χ^2/df = 261/235

(R. Gran)



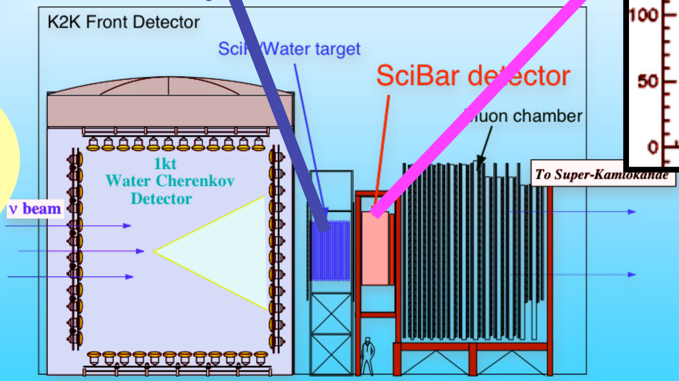
SciBar, ^{12}C (Q^2>0.2):

- M_A = 1.14 ± 0.11 GeV
- χ^2/df = 118.7/105



(F. Sanchez, NuInt07)

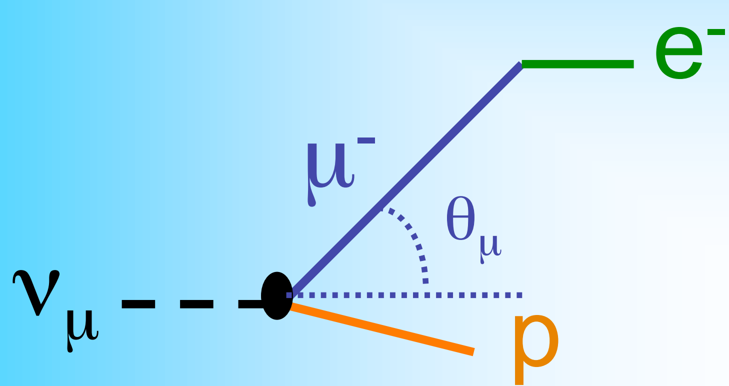
1st determination of M_A on a water target!

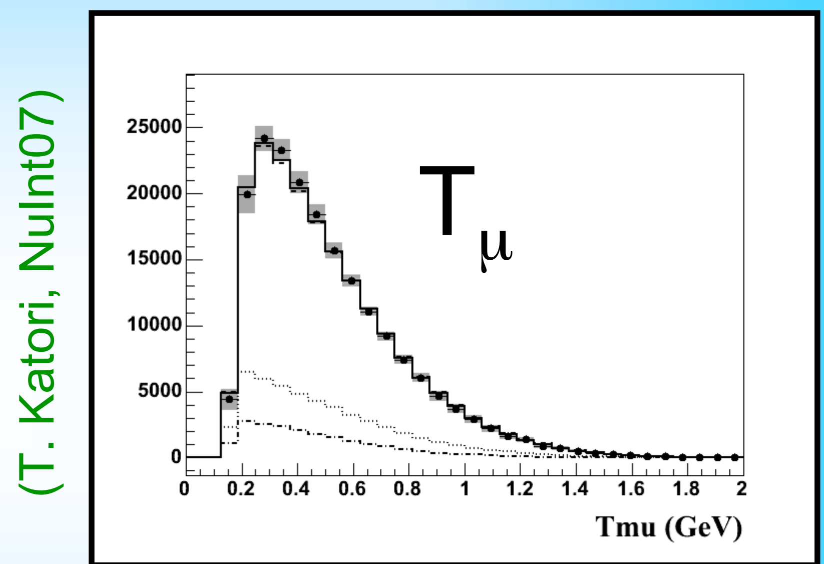


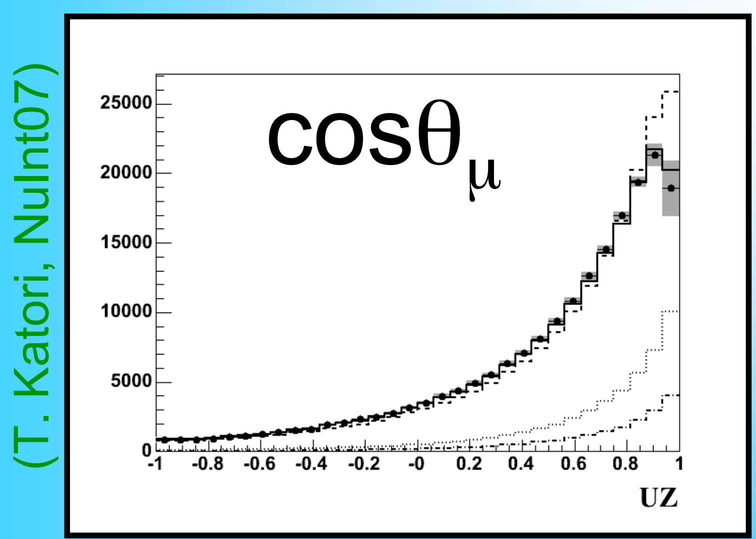
10% measurements

MiniBooNE QE Selection

- measure visible T_μ, θ_μ from Cerenkov light produced by μ







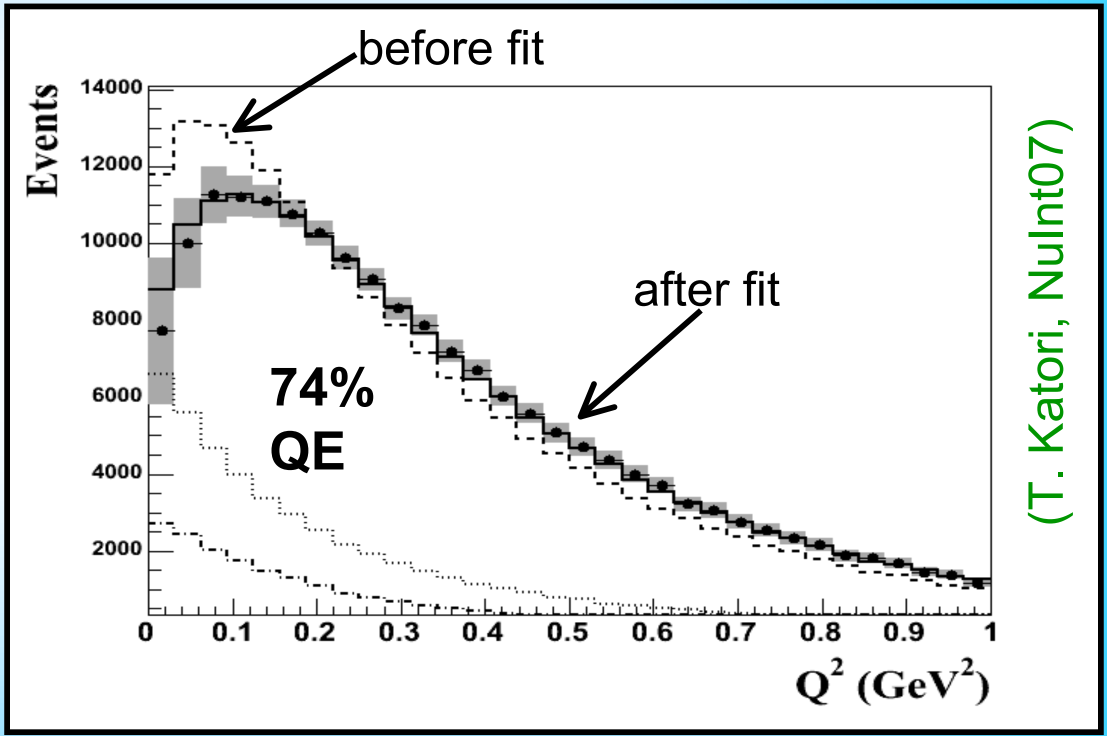
- events tagged by $\mu^- \rightarrow e^-$ decay, not by reconstructing proton
- successful because of Booster ν flux (starting with lower non-QE bkg)

MiniBooNE M_A Fit Results

MiniBooNE, ^{12}C (Q^2>0):

- M_A = 1.23 ± 0.20 GeV
- κ = 1.019 ± 0.011
- χ^2/df = 32.8/30

NEW!



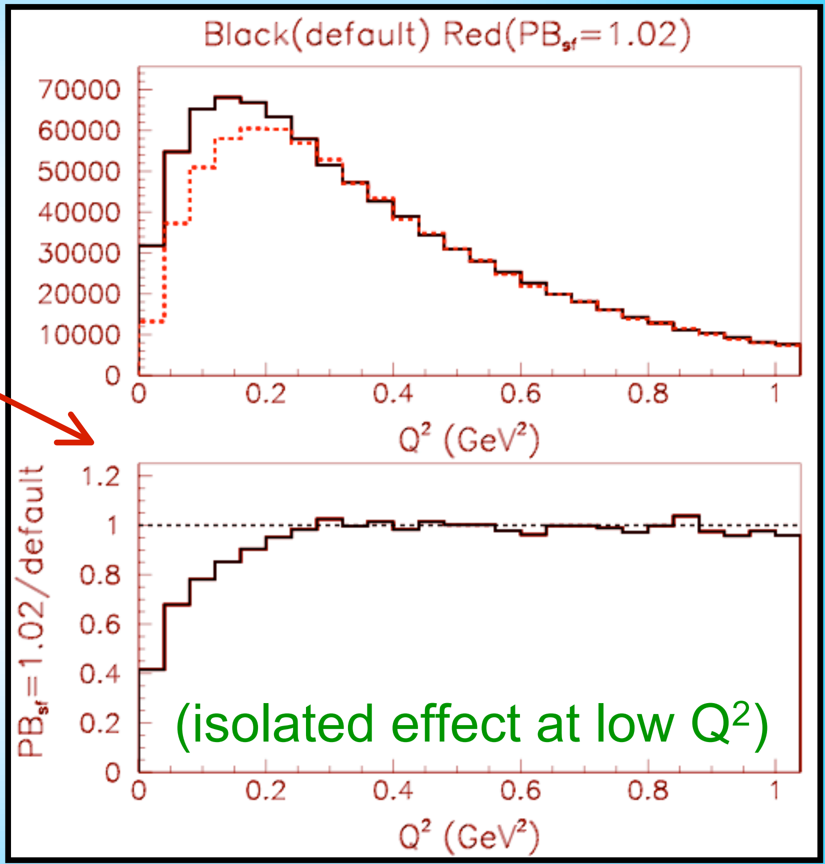
(T. Katori, NuInt07)

by fitting Q^2 distribution in the data, which is sensitive to M_A

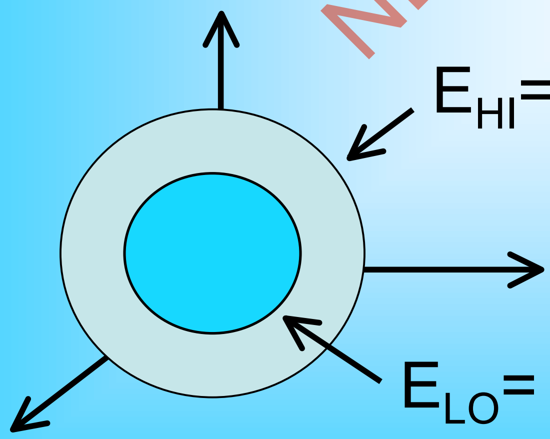
MiniBooNE M_A Fit Results

MiniBooNE, ^{12}C ($Q^2>0$):

- M_A = 1.23 ± 0.20 GeV
- κ = 1.019 ± 0.011
- χ^2/df = 32.8/30



NEW!



$E_{HI} = \sqrt{p_F^2+M^2}$

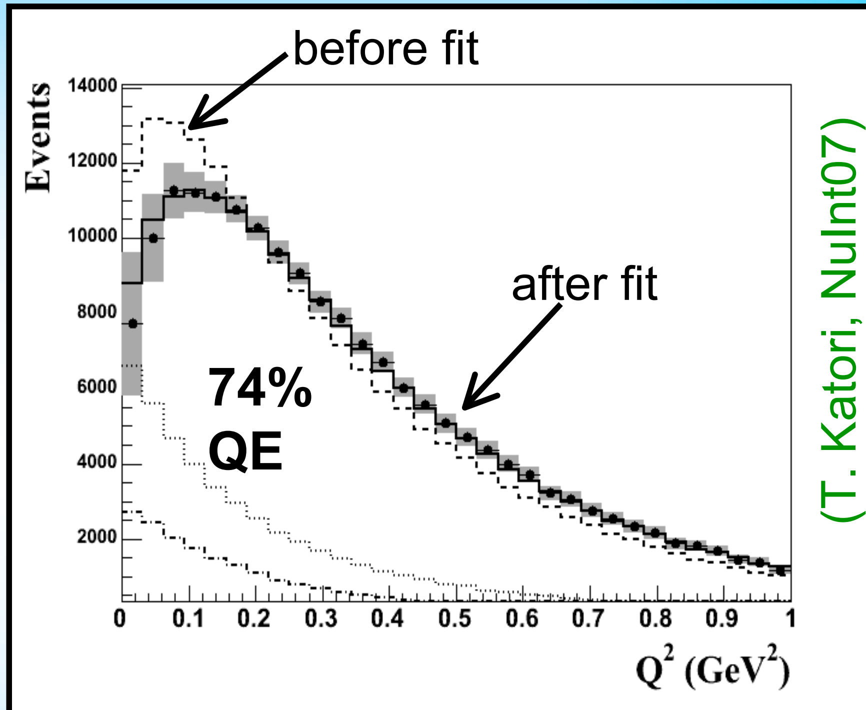
$E_{LO} = \kappa\sqrt{p_F^2+M^2} - \omega_{eff}$

MiniBooNE M_A Fit Results

MiniBooNE, ^{12}C (Q^2>0):

- M_A = 1.23 ± 0.20 GeV
- κ = 1.019 ± 0.011
- χ^2/df = 32.8/30

NEW!



(T. Katori, NuInt07)

MiniBooNE, ^{12}C (Q^2>0.25):

- M_A = 1.25 ± 0.12 GeV
- χ^2/df = 26.6/22

more standard approach
(10% measurement)

MiniBooNE M_A Fit Results

MiniBooNE, ^{12}C ($Q^2>0$):

- M_A = 1.23 ± 0.20 GeV
- κ = 1.019 ± 0.011
- χ^2/df = 32.8/30

publication on these results will be available in a few days (keep an eye out)

NEW!

important for MiniBooNE $\nu_\mu \rightarrow \nu_e$ oscillation analysis

MiniBooNE, ^{12}C ($Q^2>0.25$):

- M_A = 1.25 ± 0.12 GeV
- χ^2/df = 26.6/22

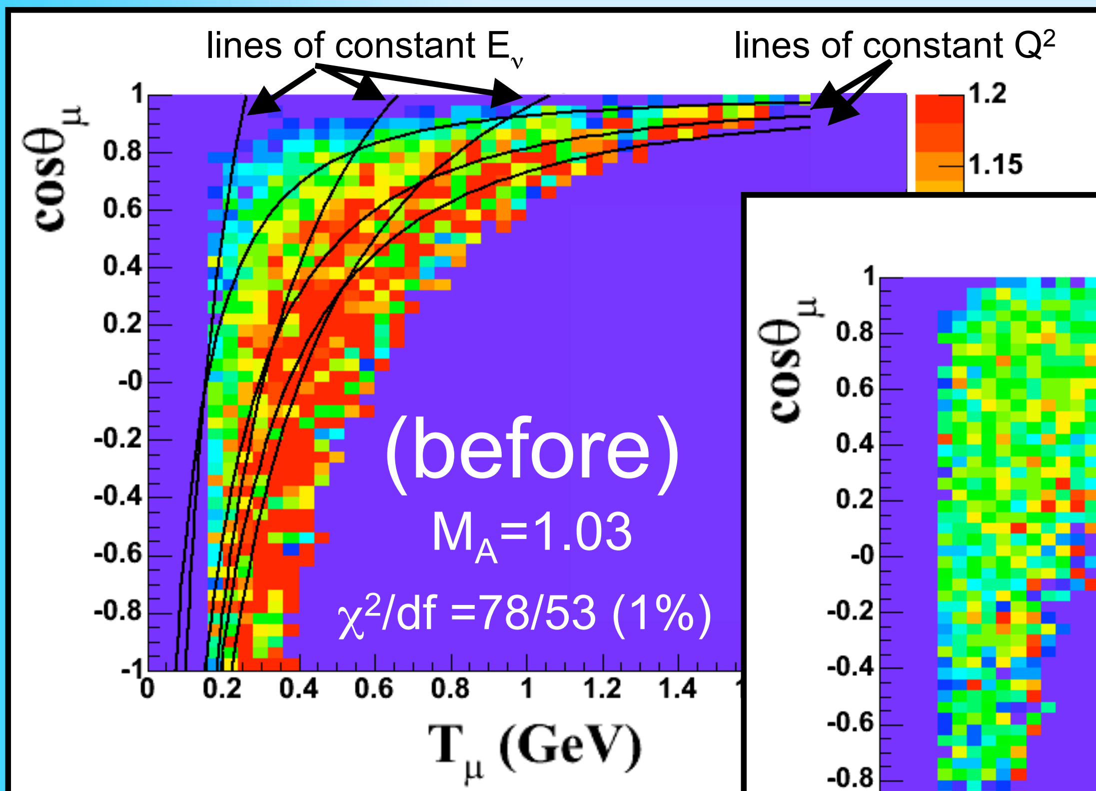
want to be able to describe QE events throughout kinematic space

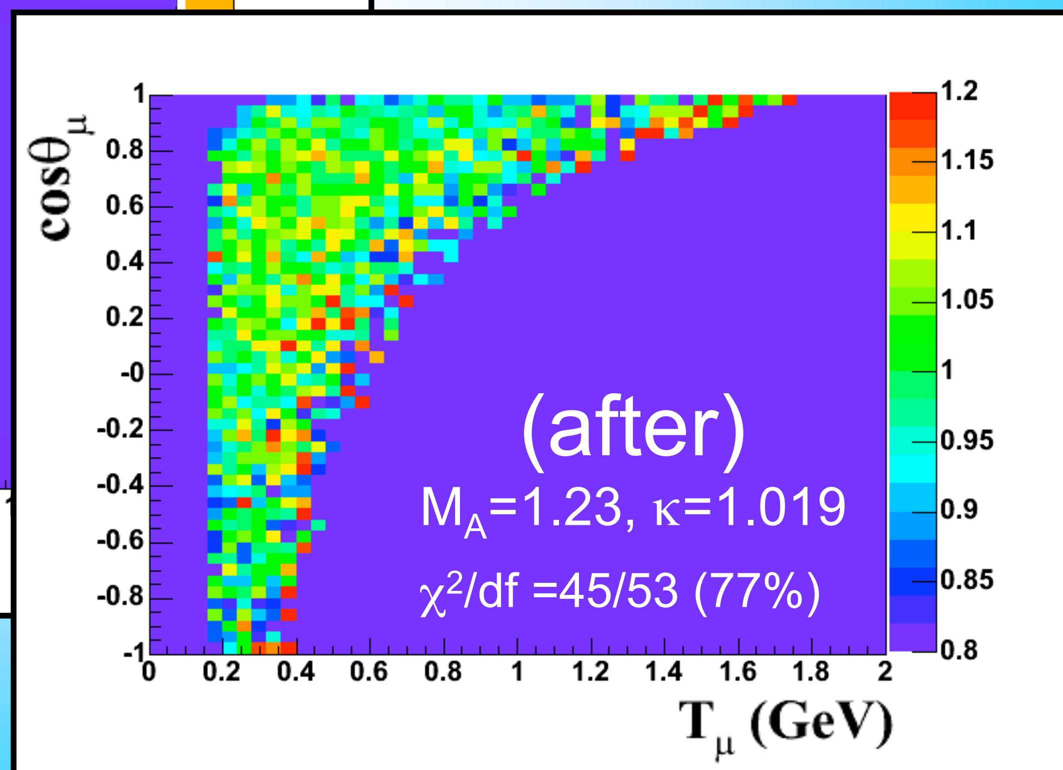
MiniBooNE Verification

- one of advantages of having high stats is can plot in 2D

  (197k ν_μ QE events)

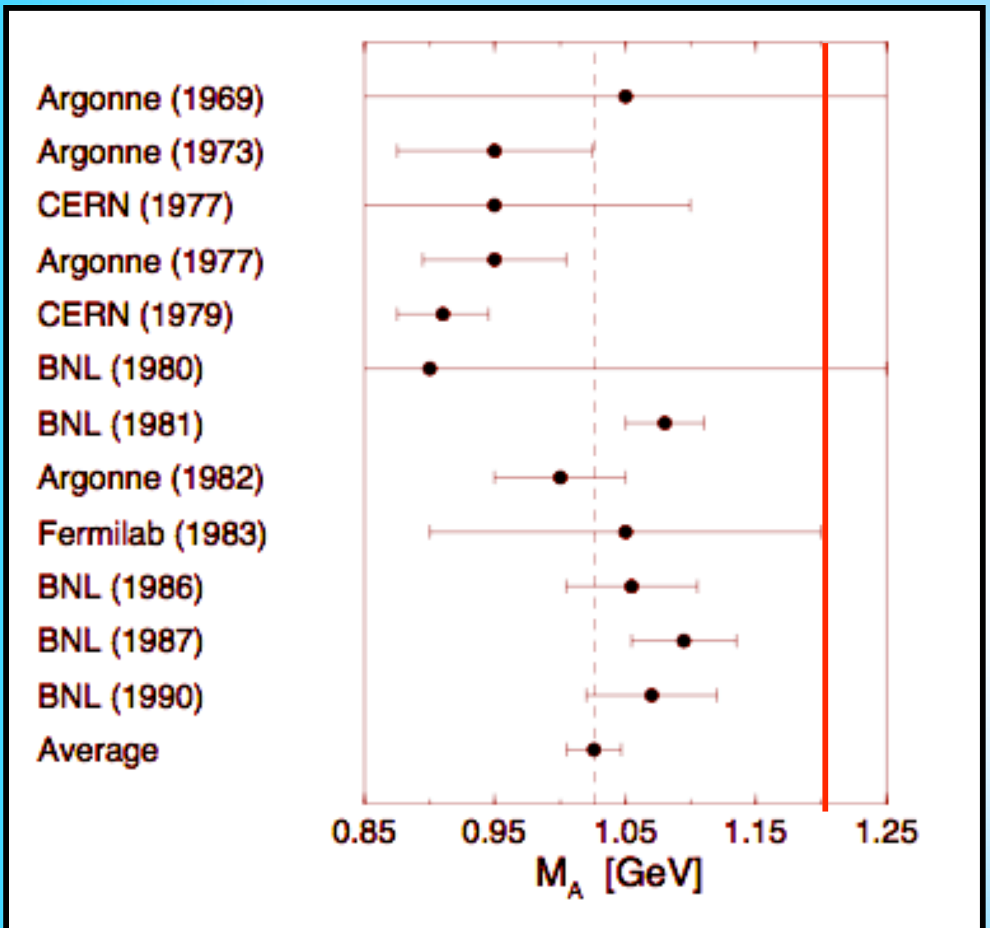
data/MC agreement in 2D after fitting in 1D





(T. Katori, NuInt07)

Why is this Interesting?



world avg: M_A = 1.03 ± 0.02 GeV
J.Phys.**G28**, R1 (2002)

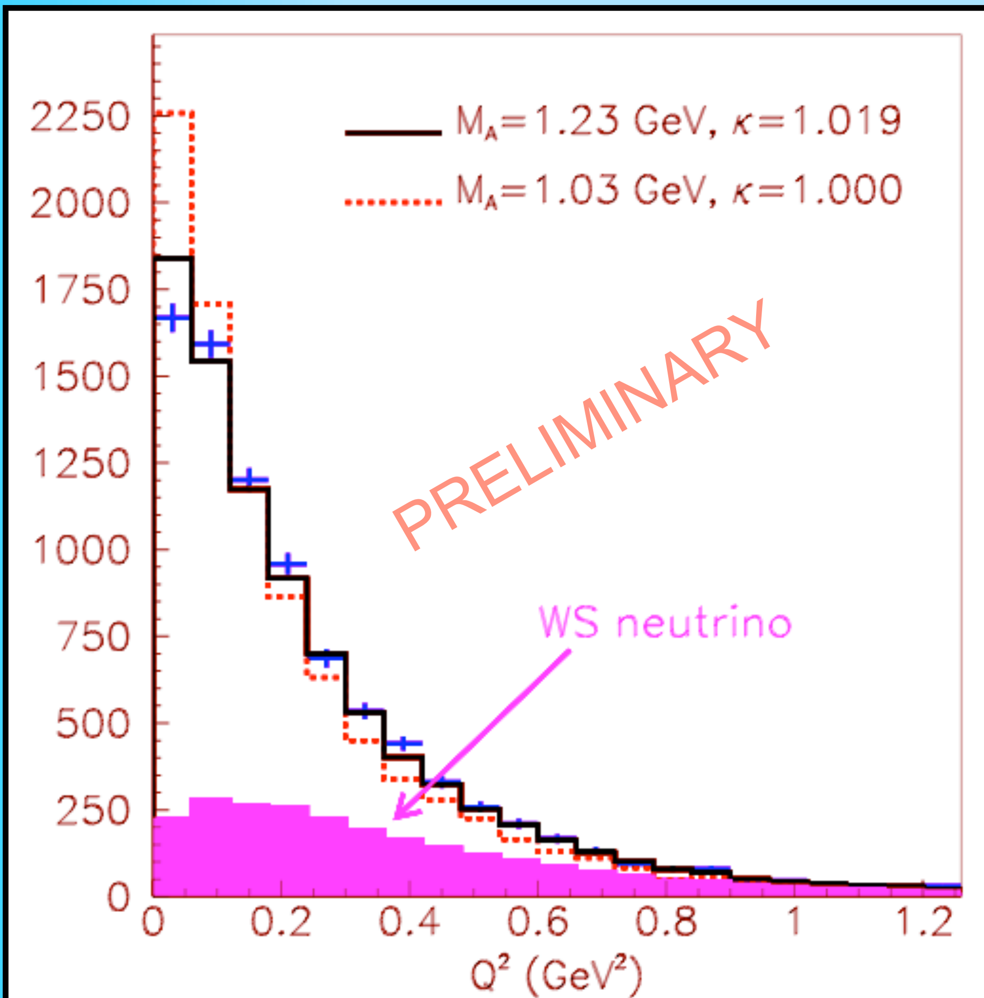
- **K2K SciFi** (H_2O, $Q^2>0.2$)
  Phys. Rev. **D74**, 052002 (2006)
  M_A=1.20 ± 0.12 GeV
- **K2K SciBar** (^{12}C, $Q^2>0.2$)
  M_A=1.14 ± 0.11 GeV
- **MiniBooNE** (^{12}C, $Q^2>0.25$)
  M_A=1.25 ± 0.12 GeV

- new results consistent
- 10% measurements of M_A
- modern data measuring systematically higher M_A

?

(measuring an "effective M_A")

MiniBooNE Antineutrino QE Data



$\bar{\nu}_\mu \, p \rightarrow \mu^+ \, n$

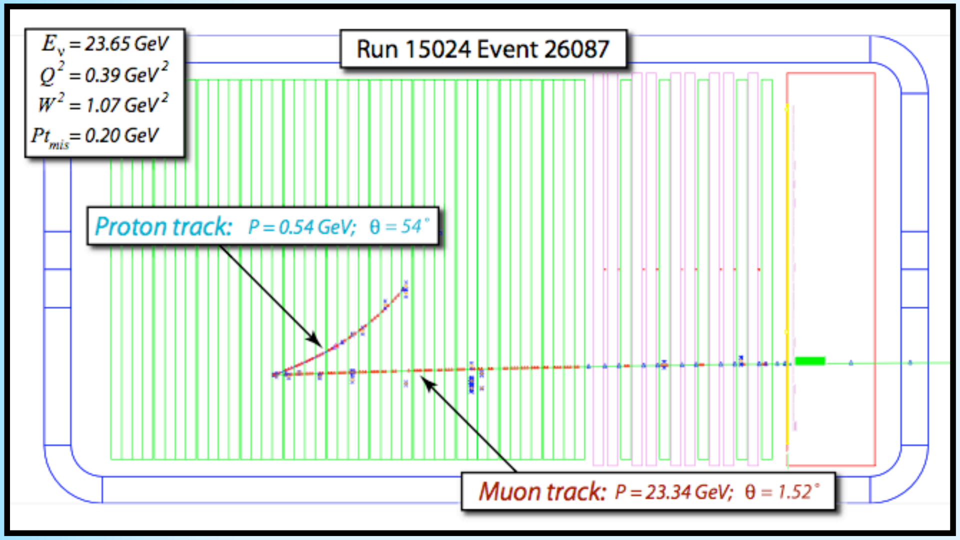
NEW!

- MiniBooNE switched to $\bar{\nu}$ running in Jan 2006
- 8,772 $\bar{\nu}_\mu$ QE events
- expect ~ x2 more by Aug
- comforting to see that ν mode pars seem to successfully describe the MiniBooNE $\bar{\nu}$ data

(if didn't get this … trouble)

QE Scattering at NOMAD

- **~10,000 candidate ν_μ QE events from 2-track sample**
  - 70% QE purity, 28% efficiency



$\nu_\mu\, n \rightarrow \mu^-\, p$

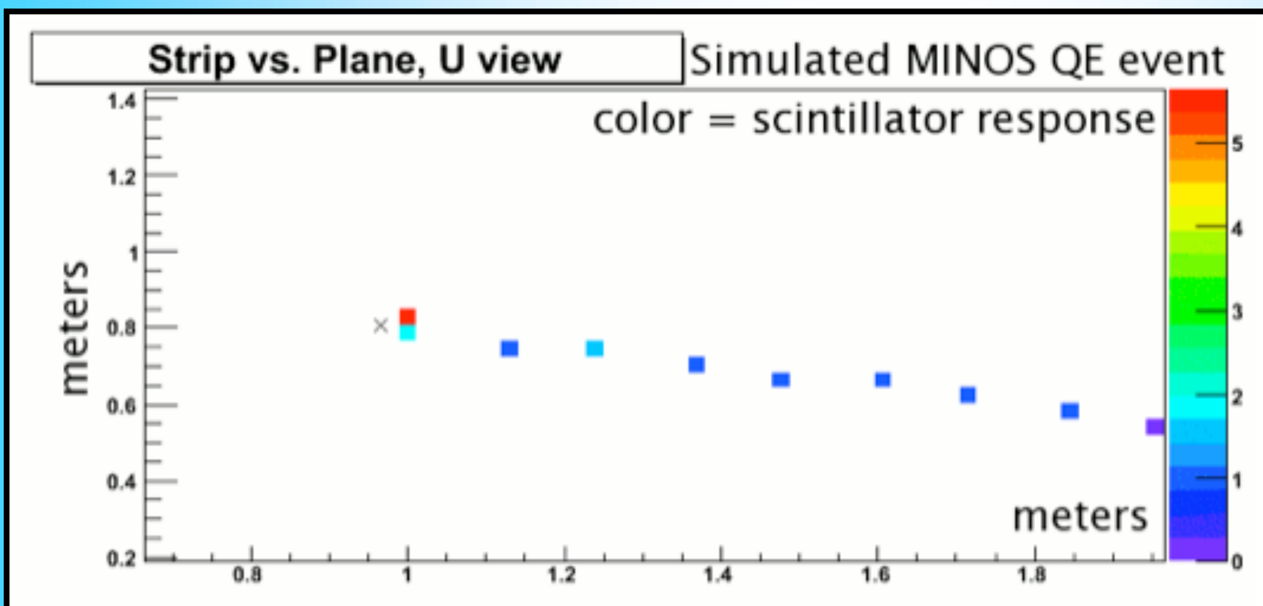
(R. Petti, NOMAD)

- **can measure QE σ on ^{12}C from $3 < E_\nu < 100$ GeV**
  - higher energy reach than K2K, MiniBooNE
  - might expect lower M_A?! worth keeping an eye on
  - publication on final results expected in next few months

QE Events at MINOS

- expects ~800,000 ν_μ QE events <u>on iron</u>

  - predict ~70% QE purity
  - will be interesting to see if can extract M_A from this data (1st on Fe)



(R. Gran, D. Bhattacharya, NuInt07)

$\nu_\mu\, n \rightarrow \mu^-\, p$

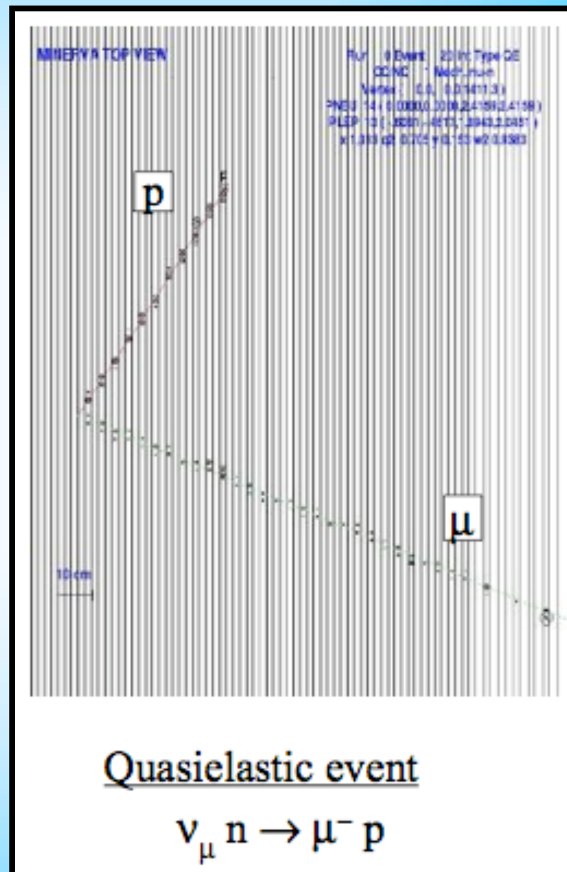
exciting!

QE Scattering at MINERvA

- expect ~800,000 ν_μ QE events in carbon (4 year run), up to 20 GeV

  - high efficiency: 74%
  - and purity: 77%

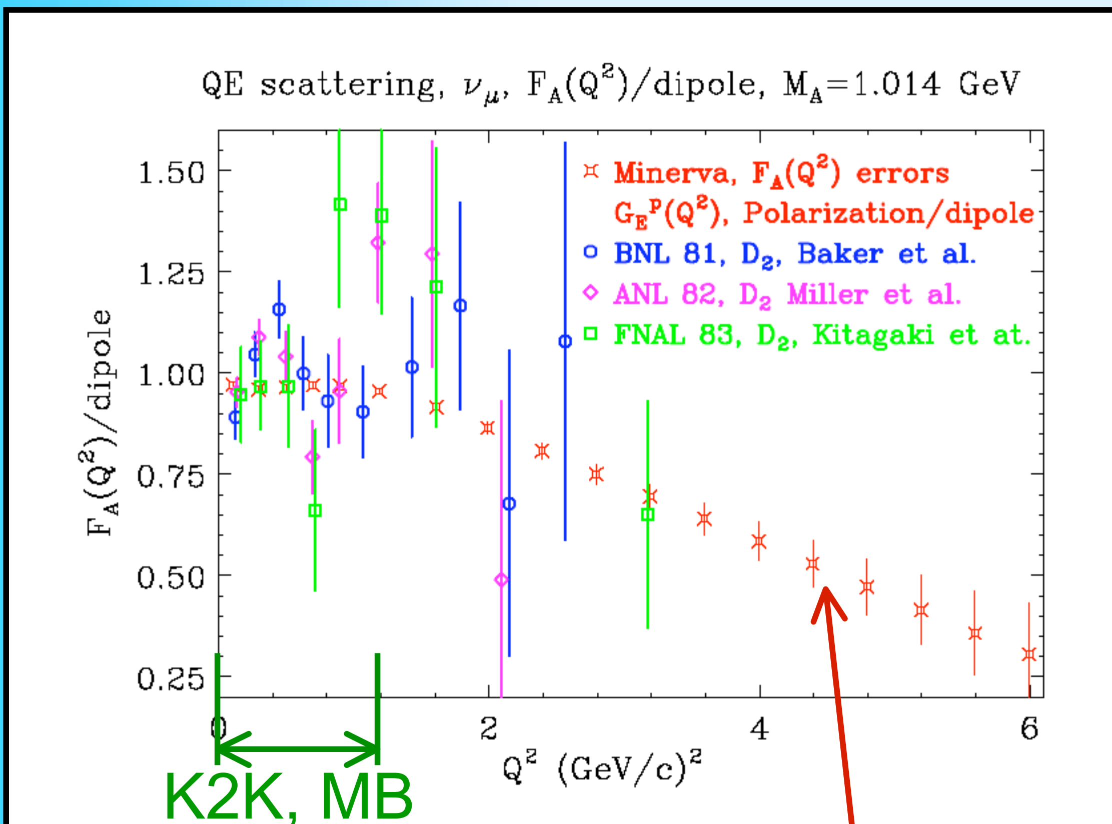
- plus, event samples on nuclear targets C, Fe, Pb



example of a simulated QE event in MINERvA detector

MINERvA QE Measurements

- very precise determination of axial form factor $F_A(Q^2)$



MINERvA projection

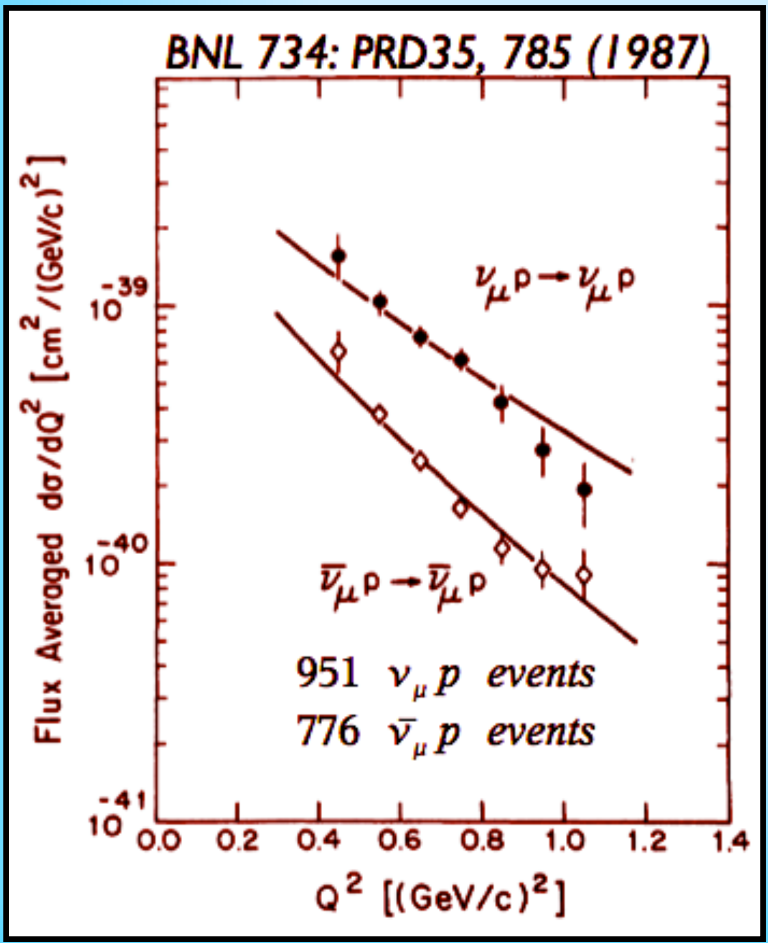
$$F_A(Q^2) = \frac{g_A}{(1+Q^2/M_A{}^2)^2}$$

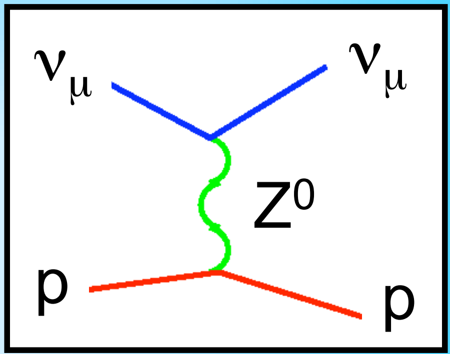
- is the axial form factor really dipole?
- access high Q^2 region
- study medium effects

really important to settle this!

NC Elastic Scattering

- only existing measurement of absolute σ





ν_μ p $\rightarrow$ ν_μ p
n $\rightarrow$ n

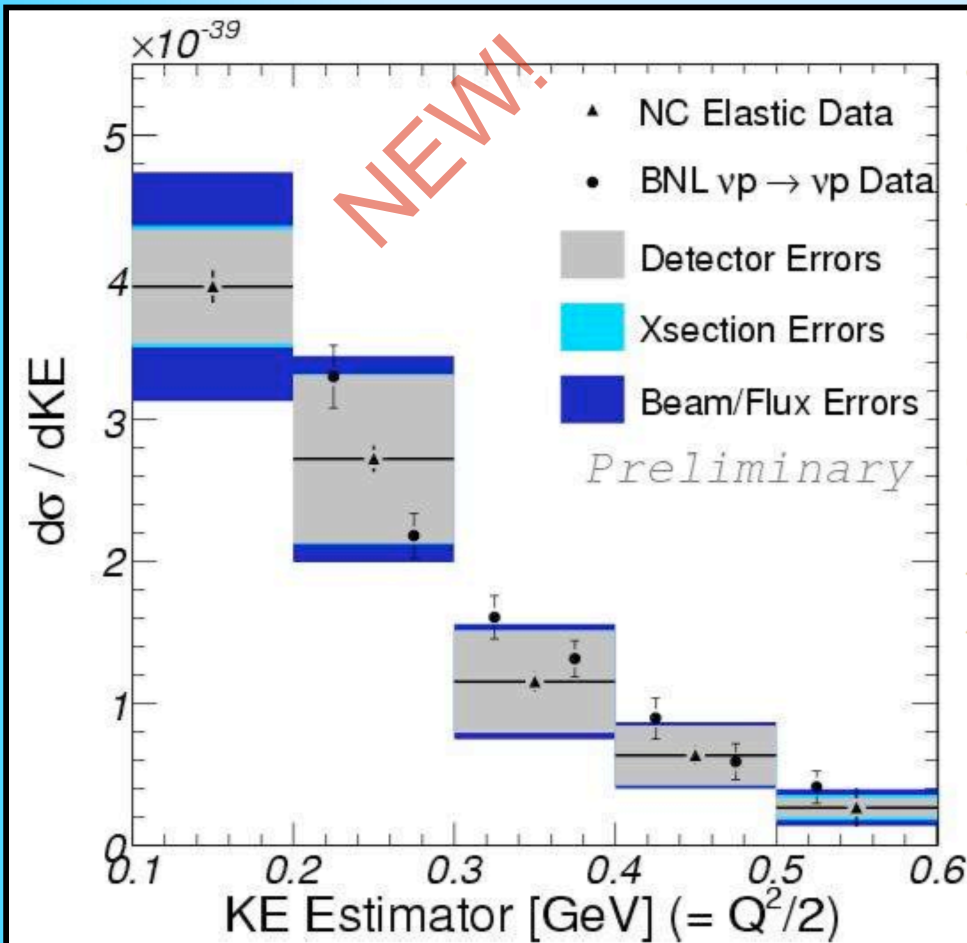
- BNL E734 measured NC elastic scattering σ as a function of Q^2

- how does this compare against modern data?

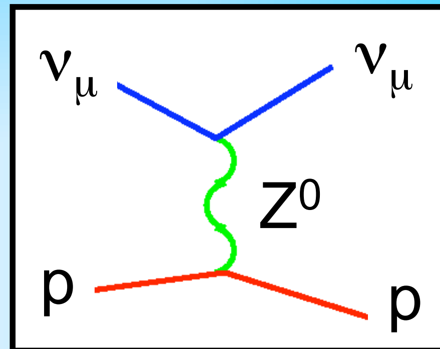
Sam Zeller, 06/01/07

MiniBooNE NC Elastic Scattering

- can select an 84% pure NC EL sample (n+p)



(C. Cox, NuInt07)



ν_μ p → ν_μ p
n → n

- ~10% of total sample
- 1st differential σ results from MiniBooNE
- yesterday was 1st time shown outside the collab

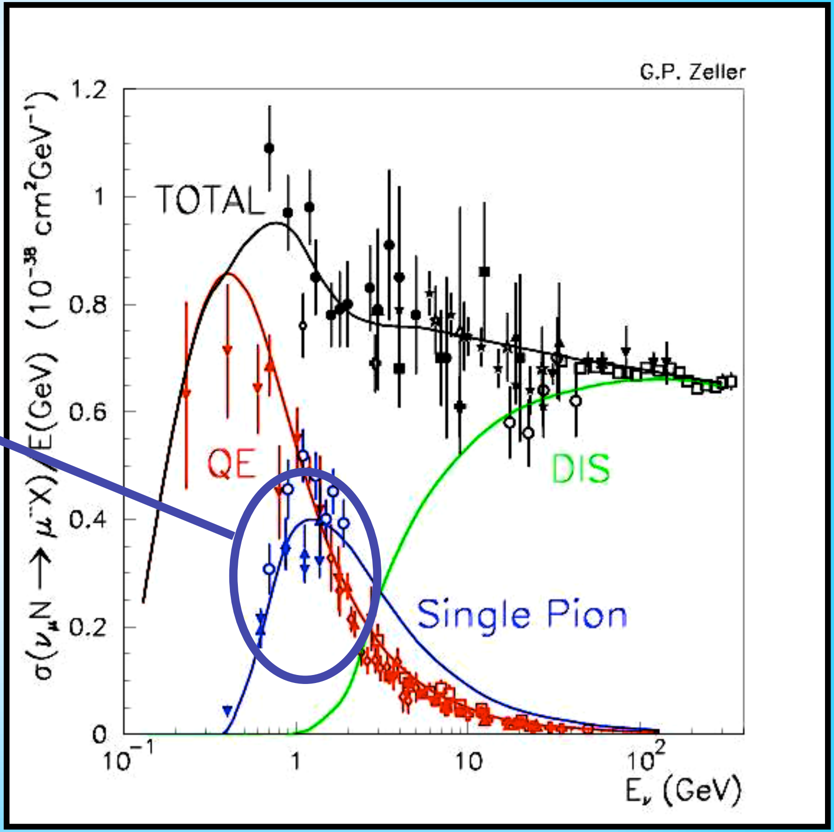
Low Energy Neutrino Interactions

- moving up in energy …

(1) quasi-elastic (QE)
- dominates $E_\nu \lesssim 1$ GeV

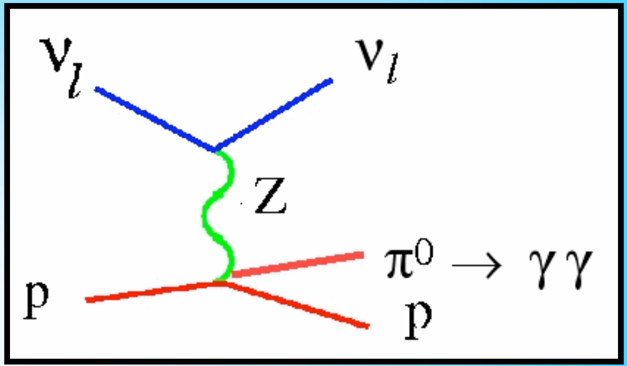
(2) NC, CC 1π production
- NC π^0 (res+coh)
- CC π^+ (res+coh)
- CC π^0 (res)

(3) CC inclusive, DIS
- dominates $E_\nu \gtrsim 5$ GeV



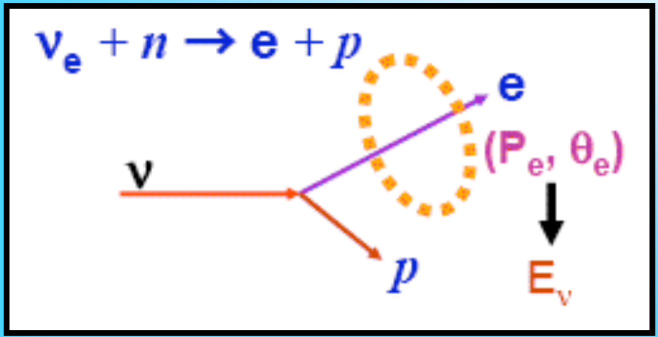
NC $1\pi^0$ Production

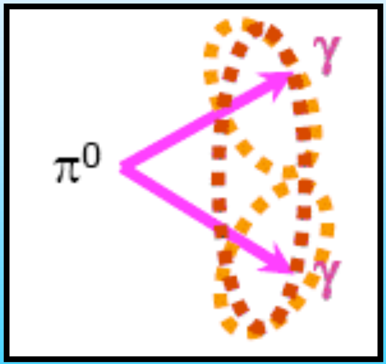
Why important?



$\nu_\mu \, N \to \nu_\mu \, N \, \pi^0$

- **important for neutrino oscillation experiments**
  - poses a serious background to $\nu_\mu \to \nu_e$ appearance searches, θ_{13}
    (can look electron-like; in past, primary method for estimating = MC)

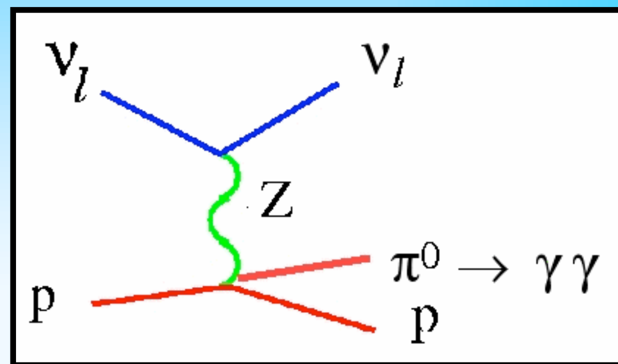




- have to control π^0s very well since directly impacts sensitivity

NC $1\pi^0$ Production

Why important?



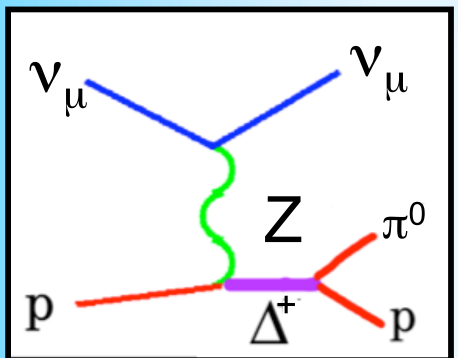
$\nu_\mu\, N \to \nu_\mu\, N\, \pi^0$

- **important for neutrino oscillation experiments**
  - poses a serious background to $\nu_\mu \to \nu_e$ appearance searches, θ_{13} (can look electron-like; in past, primary method for estimating = MC)

- **interesting on their own**
  - π^0 data can tell us about mode of production (resonant or coherent)

NC $1\pi^0$ Production

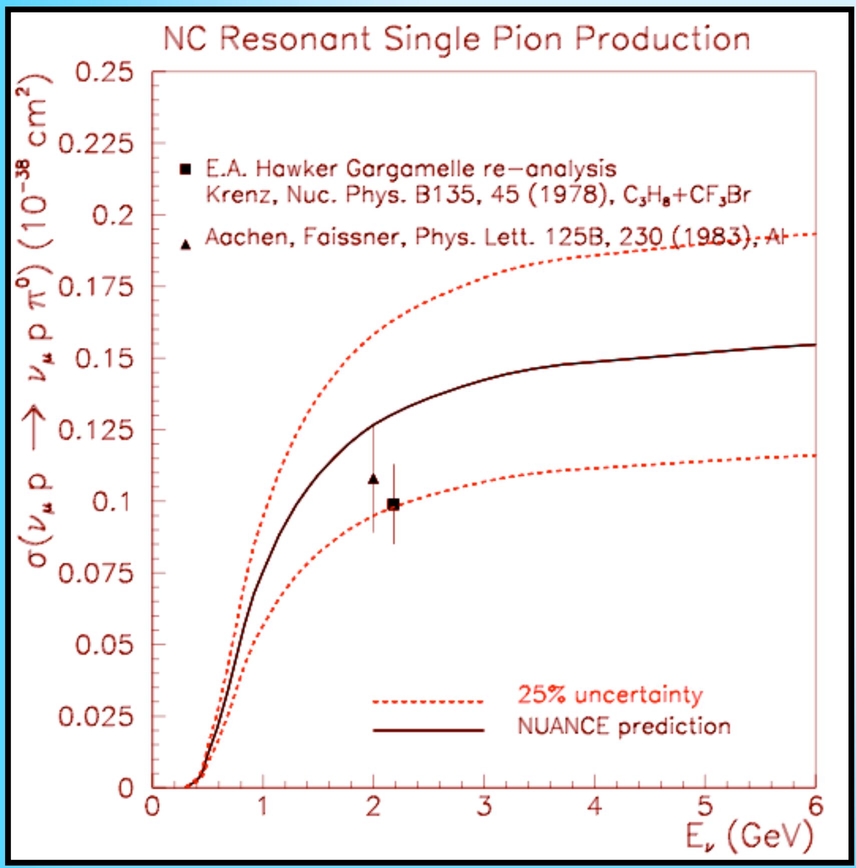
resonant π^0 production (dominant)   coherent π^0 production



- Δ, N* baryon resonances, which decay to Nπ
- prominent resonance = $\Delta(1232)$

NC $1\pi^0$ Production

resonant π^0 production (dominant) coherent π^0 production



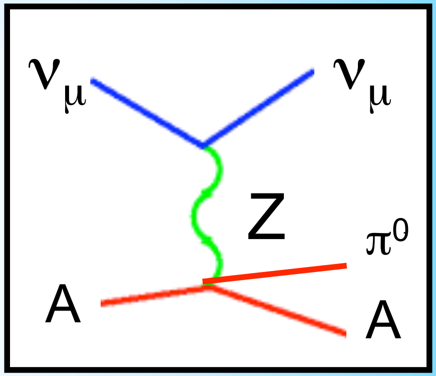
- 2 measurements at 2 GeV
- together, < 500 events

(neutrino osc exps typically assign uncertainties on this σ anywhere in 25-40% range)

NC $1\pi^0$ Production

resonant π^0 production (dominant)

coherent π^0 production

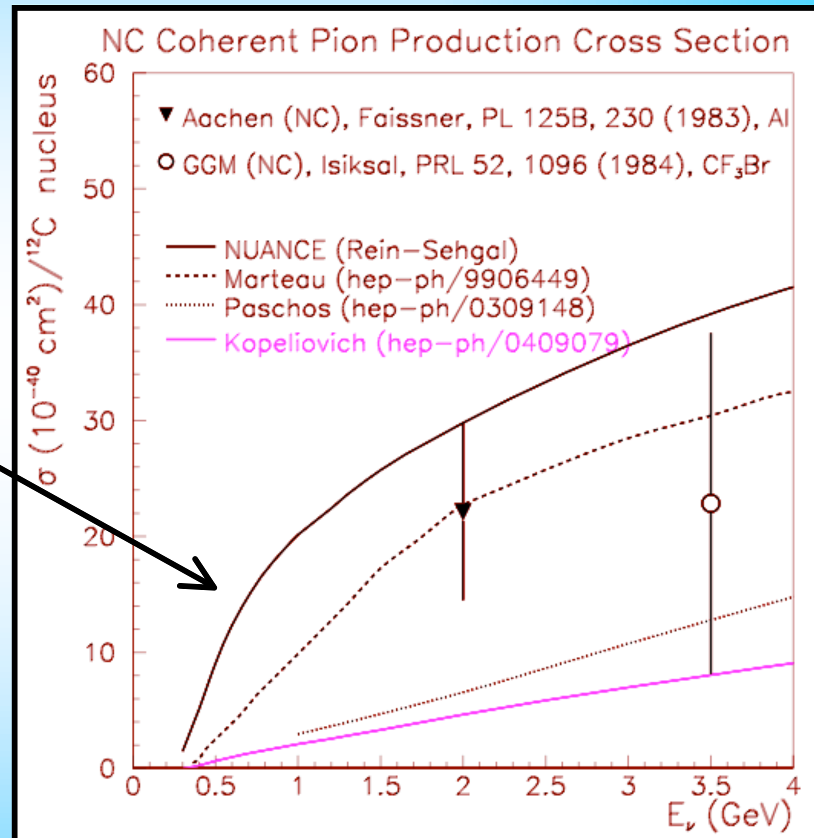


- occurs at ~20% resonant rate
- distinct exp'l signature
- nucleus stays in tact,
  forward emitted π, low Q^2
- 1st considered because
  dominant bkg to $\nu_\mu e \to \nu_\mu e$

NC $1\pi^0$ Production

resonant π^0 production (dominant)

coherent π^0 production



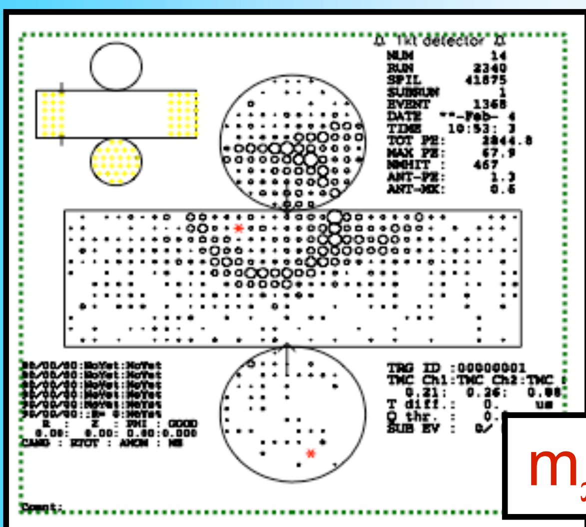
models predict wide range

(typically, 100% σ uncertainty assumed for this process)

(experiments can extract coherent scattering component by looking for very forward π production … will come back to this later in the talk)

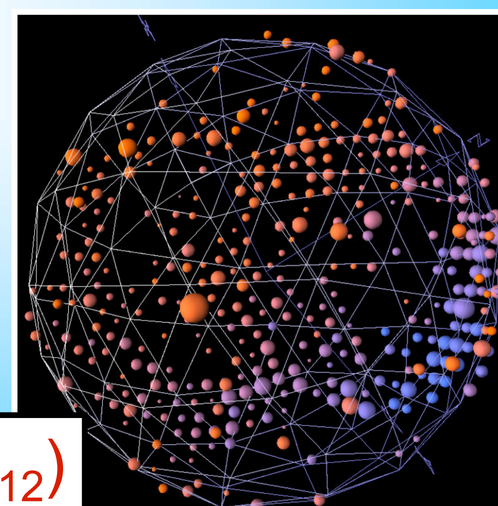
Modern NC π^0 Analyses

K2K	MiniBooNE
1kton Cerenkov (H_2O)	800 ton Cerenkov (CH_2)
π^0 momentum spectrum	π^0 momentum spectrum
NC π^0/CC σ ratio	**NC π^0 COH/RES σ ratio**



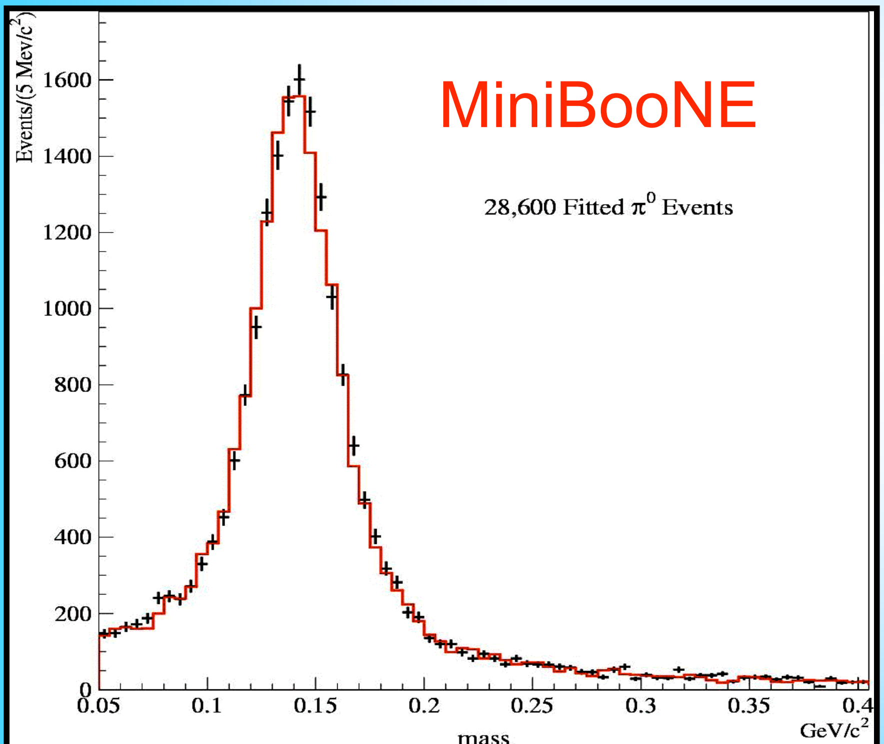
$$\pi^0 \rightarrow \gamma\gamma$$

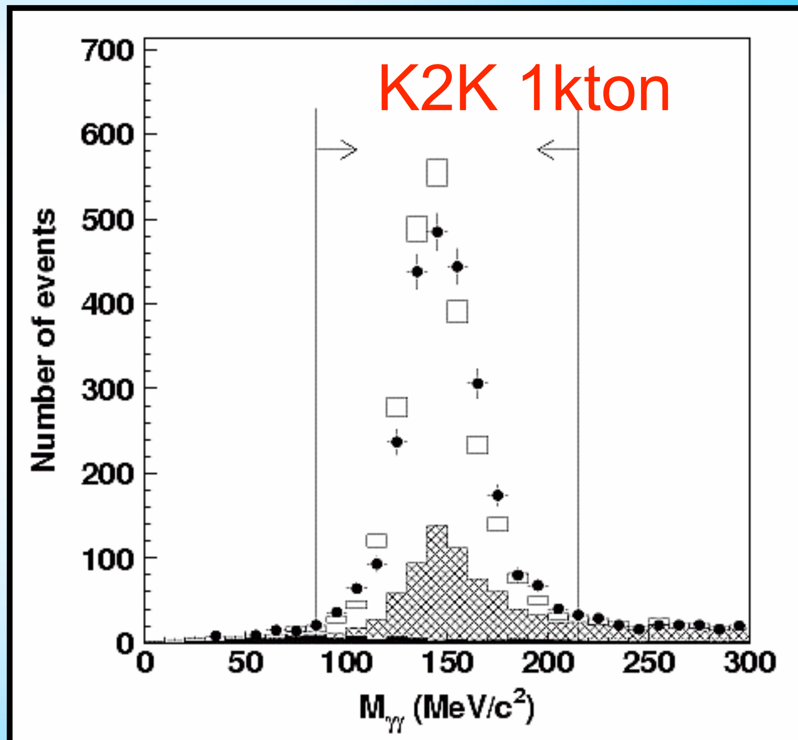
$$m_\pi^{\,2} = 2E_{\gamma 1}E_{\gamma 2}(1-\cos\theta_{12})$$



Modern NC $1\pi^0$ Data

- π^0 mass peak clearly visible
- this is the largest sample of NC $1\pi^0$ events ever collected!





- 28,600 NC π^0 events

J. Link, NuInt07

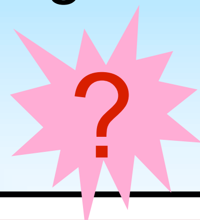
- 2,496 NC π^0 events

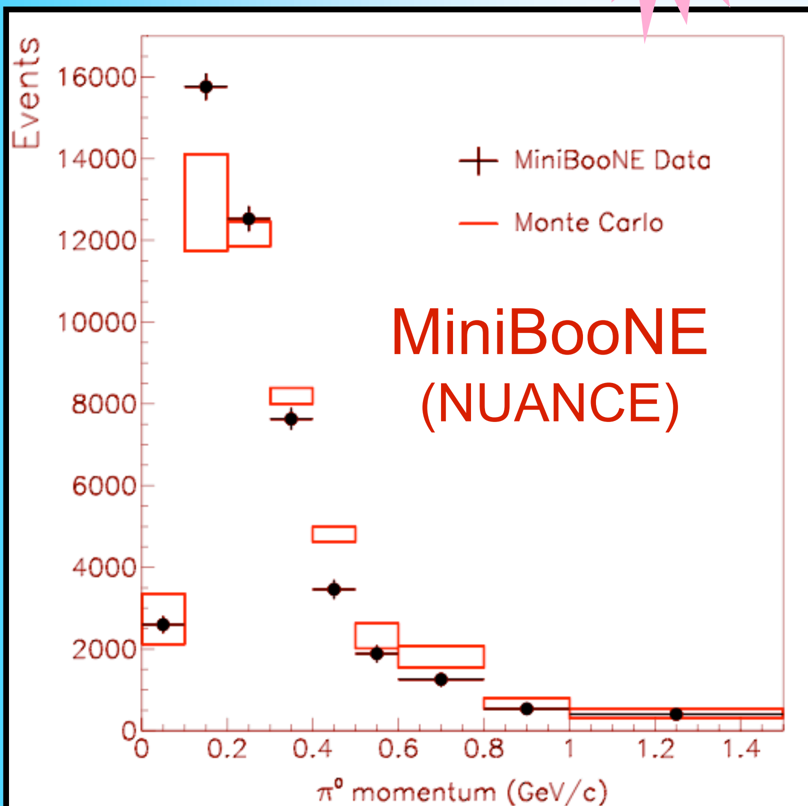
S. Nakayama *et al*., PLB**619**, 255 (2005)

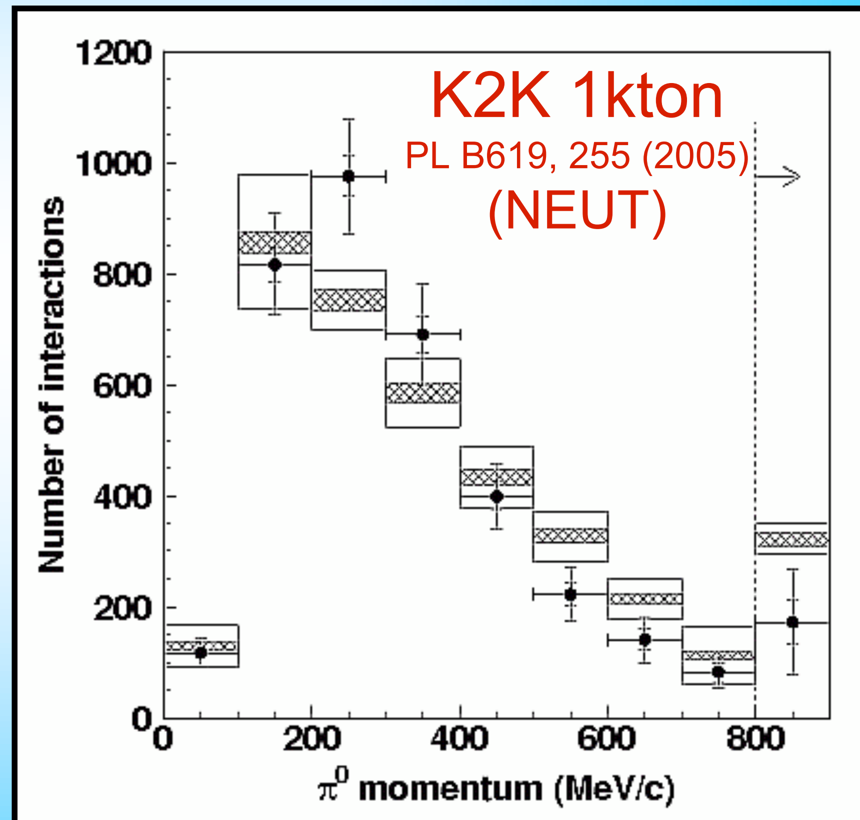
π^0 Momentum Spectra

- modern data revealing some inadequacies in present models
- FSI model?

(can give effects like this)



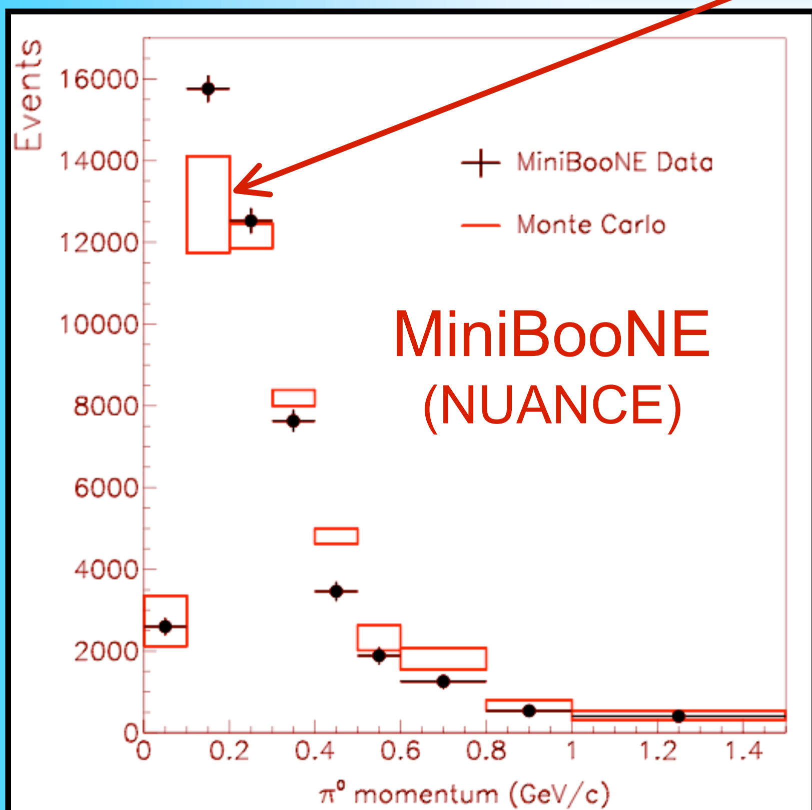




π^0 Momentum Spectra

- modern data revealing some inadequacies in present models
- FSI model?

Monte Carlo straight out of the box



important for MiniBooNE $\nu_\mu \rightarrow \nu_e$ oscillation analysis

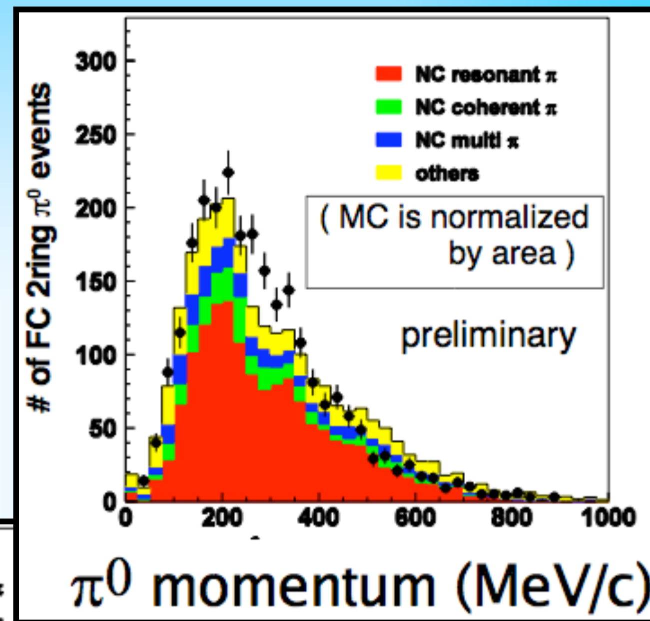
- extremely important to know how many of these there are
- provided a 10% constraint on NC π^0 production rate on CH_2

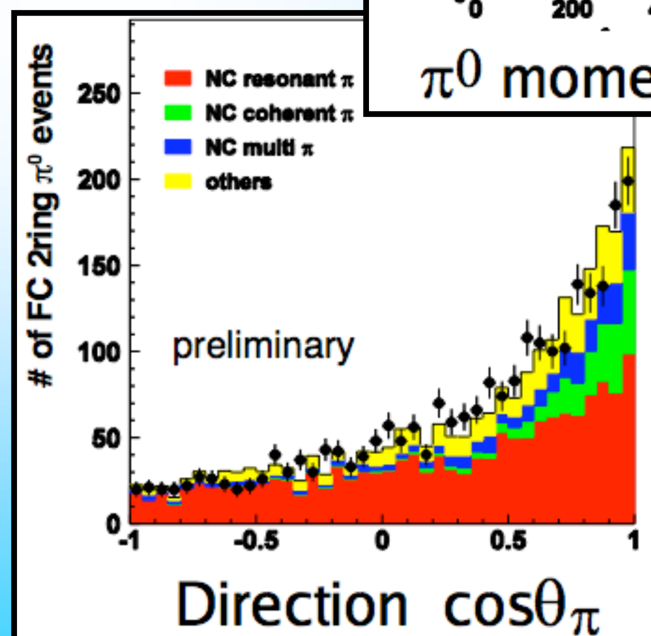
K2K NC π^0 Cross Section Results

K2K 1kton Water Cerenkov:

NC π^0/1μ ratio = 0.064 ± 0.001 (stat) ± 0.007 (syst)

- 10% measurement at <E_ν> ~ 1.3 GeV
- in good agreement w/ NEUT MC prediction
- 1st measurement on a water target





K2K NC π^0 Cross Section Results

K2K 1kton Water Cerenkov:

NC $\pi^0/1\mu$ ratio = 0.064
$\pm$ 0.001 (stat) $\pm$ 0.007 (syst)

- 10% measurement at $\langle E_\nu \rangle \sim 1.3$ GeV
- in good agreement w/ NEUT MC prediction
- 1st measurement on a water target

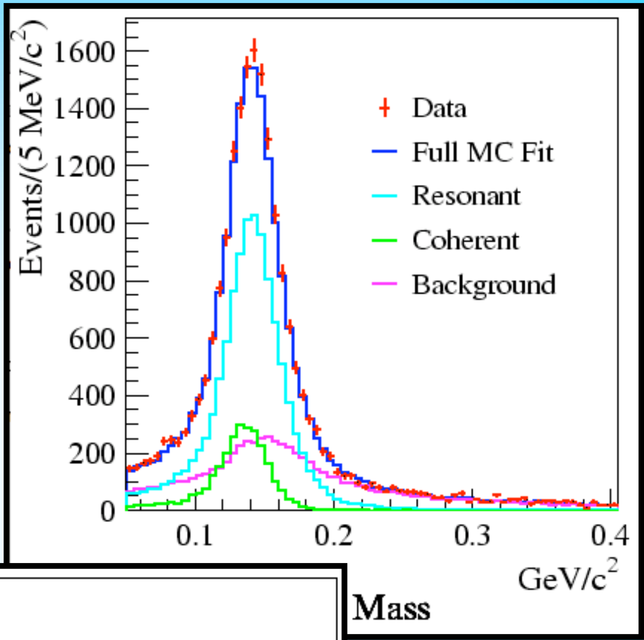
important for
Super-K distinguishing
$\nu_\mu \to \nu_\tau$ vs $\nu_\mu \to \nu_S$

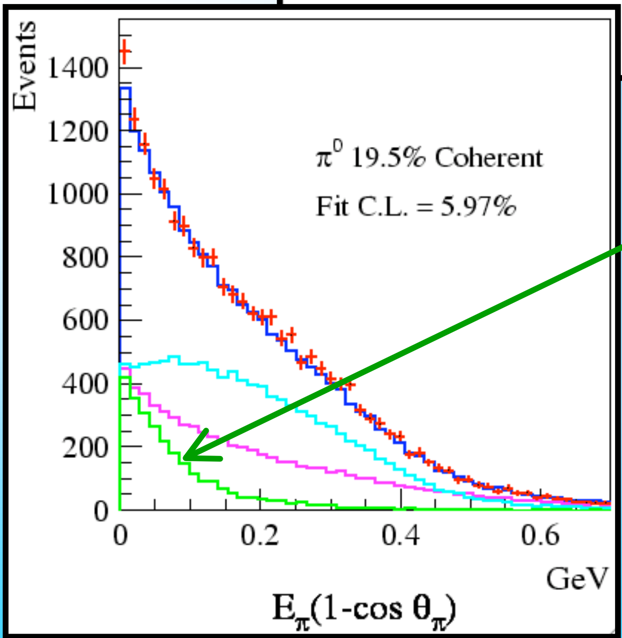
MB NC π^0 Cross Section Results

MiniBooNE:

NC π^0 COH/RES fraction
= (19.5 ± 1.1 (stat) ± 2.5 (syst))%

(J. Link, NuInt07)





- 14% measurement at $\langle E_\nu \rangle \sim 1.1$ GeV
- 1st measurement of its kind below 2 GeV
- x1.5 lower than default MC prediction (NUANCE,Rein-Sehgal)

see clear evidence for NC coherent π^0 prod

MB NC π^0 Cross Section Results

MiniBooNE:

NC π^0 COH/RES fraction
= (19.5 ± 1.1 (stat) ± 2.5 (syst))%

important for
MiniBooNE $\nu_\mu \rightarrow \nu_e$
oscillation analysis

- 14% measurement
  at $\langle E_\nu \rangle \sim 1.1$ GeV

- 1st measurement of its
  kind below 2 GeV

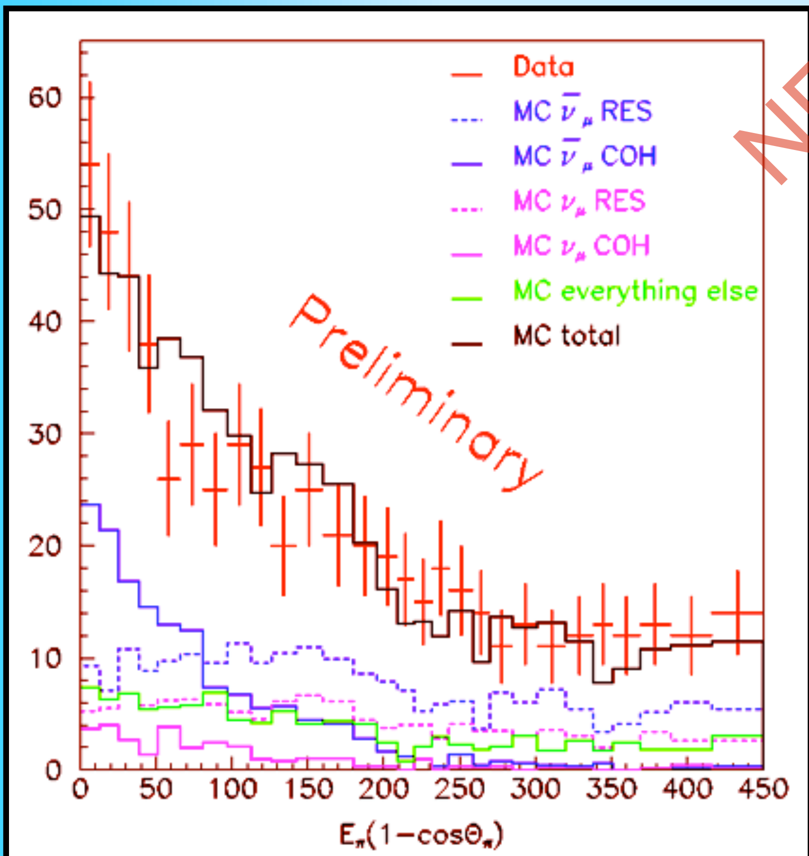
- x1.5 lower than default MC
  prediction (NUANCE,Rein-Sehgal)

recall where we started
(~100% uncertainties)

not only see in neutrino
sample, but also in new
antineutrino data …

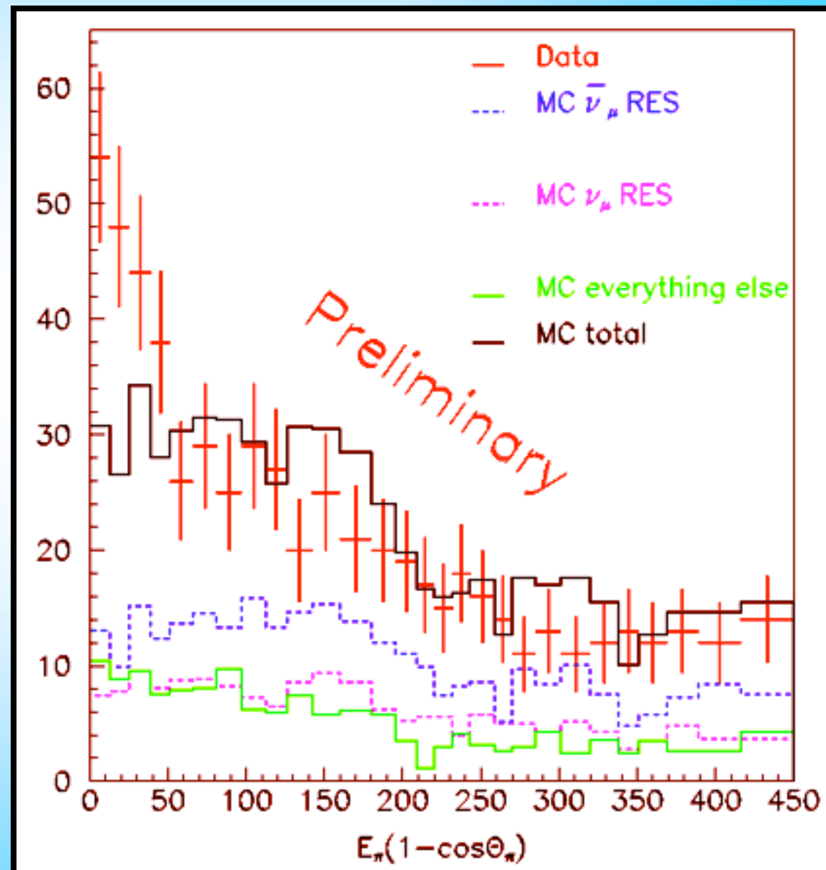
MiniBooNE Antineutrino π^0 Data

- <u>with</u> coherent production
- <u>without</u> coherent production



NEW!

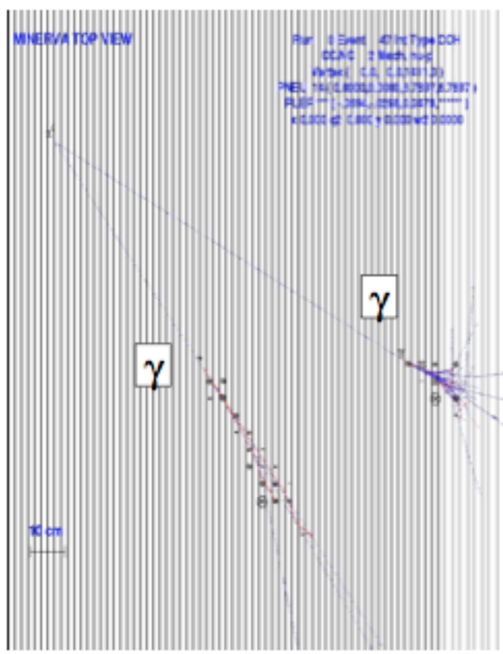
(V. Nguyen, NuInt07)



- ~900 events, enhancement at small angles suggestive of coherent prod

NC π^0 Events in MINERvA

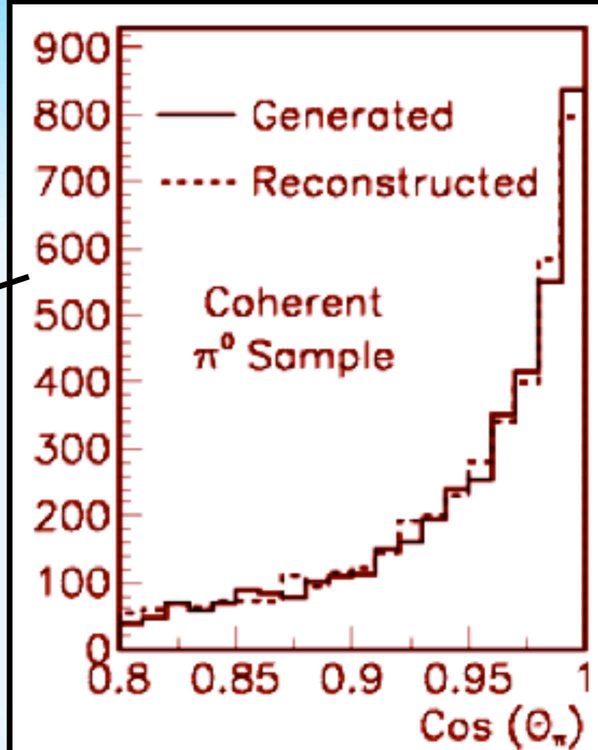
- π^0's cleanly identified, 2 γ's tracked
- EM calorimetry is pretty fantastic



Neutral Current π^0

$\nu_\mu A \rightarrow \nu_\mu A \pi^0$

measuring π angle important for separating coherent and resonant



- generated & reconstructed angular distributions nearly identical
- highlights MINERvA's excellent π^0 angular resolution

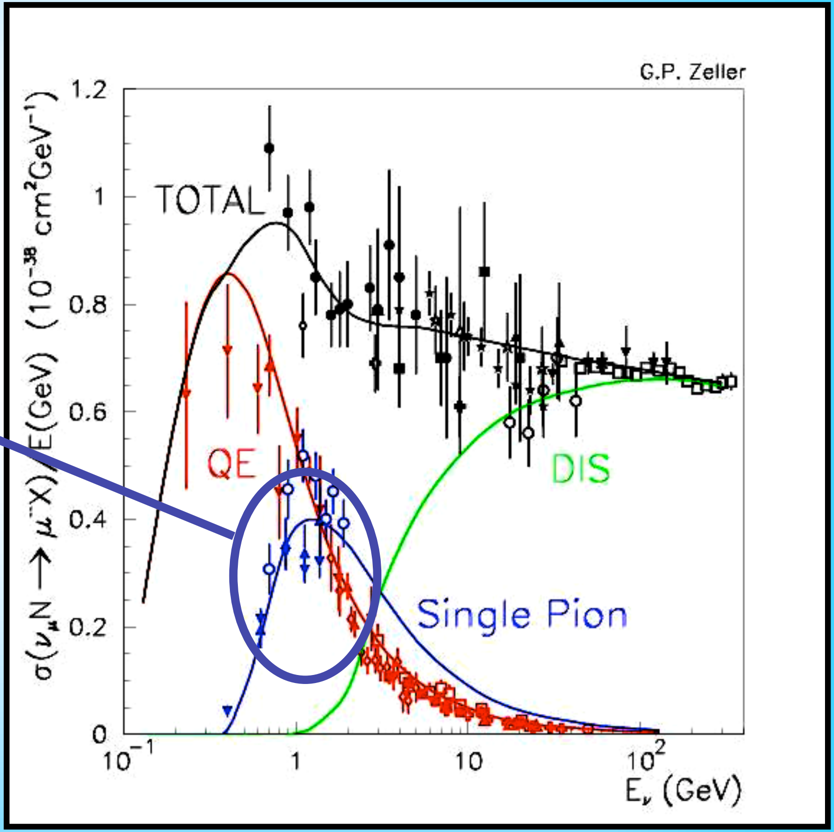
Low Energy Neutrino Interactions

- moving on to the next reaction channel …

(1) quasi-elastic (QE)
 - dominates $E_\nu \lesssim 1$ GeV

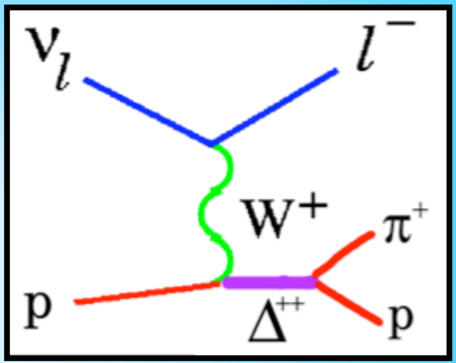
(2) NC, CC 1π production
 - NC π^0 (res+coh)
 - CC π^+ (res+coh)
 - CC π^0 (res)

(3) CC inclusive, DIS
 - dominates $E_\nu \gtrsim 5$ GeV



CC 1π Production

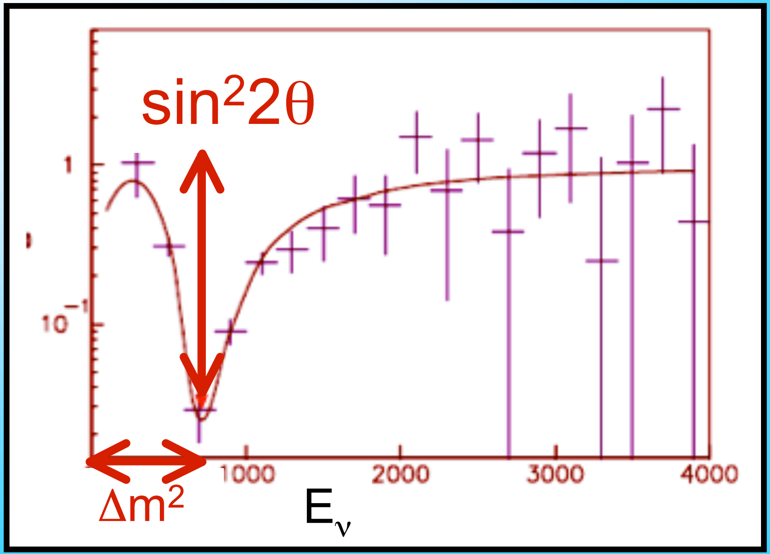
Why important?



$\nu_\mu N \rightarrow \mu^- N \pi^+$

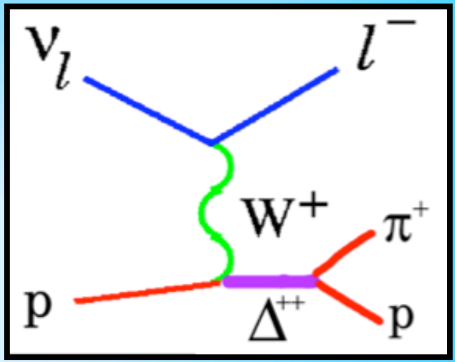
- **important for neutrino oscillation analyses**
  - poses largest bkg to QE samples (π can be absorbed in nucleus)
  - can be a large source of uncertainty for ν_μ disappearance experiments …
  - how well can subtract backgrounds maps into $\sin^2 2\theta$

(C. Walter, T2K)



CC 1π Production

Why important?



$\nu_\mu N \rightarrow \mu^- N \pi^+$

- **important for neutrino oscillation analyses**
  - poses largest bkg to QE samples (π can be absorbed in nucleus)

- **interesting on their own**
  - **CC π^+:** surpasses QE, largest σ at ~2 GeV, so can measure both resonant & coherent π^+ with high stats
  - **CC π^0:** uniquely probes resonance contribution alone (no coherent contribution in this channel)

Previous CC 1π^+ σ Measurements

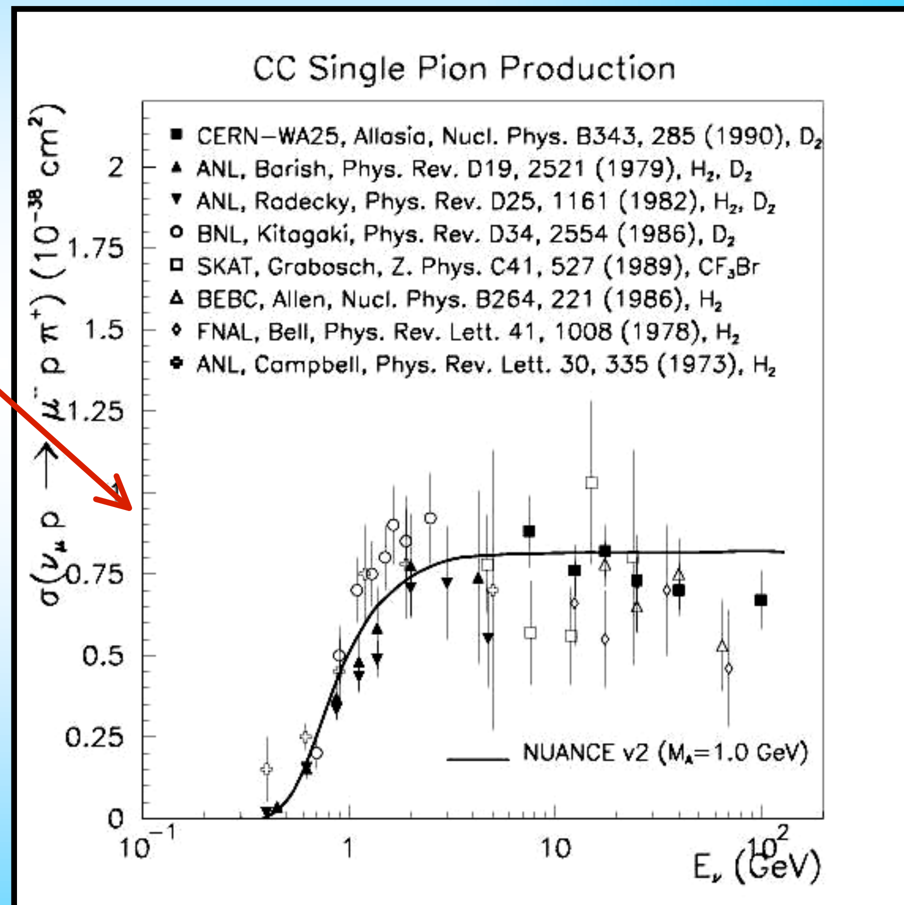
- two modes:

  $\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+\ (\Delta^{++})$

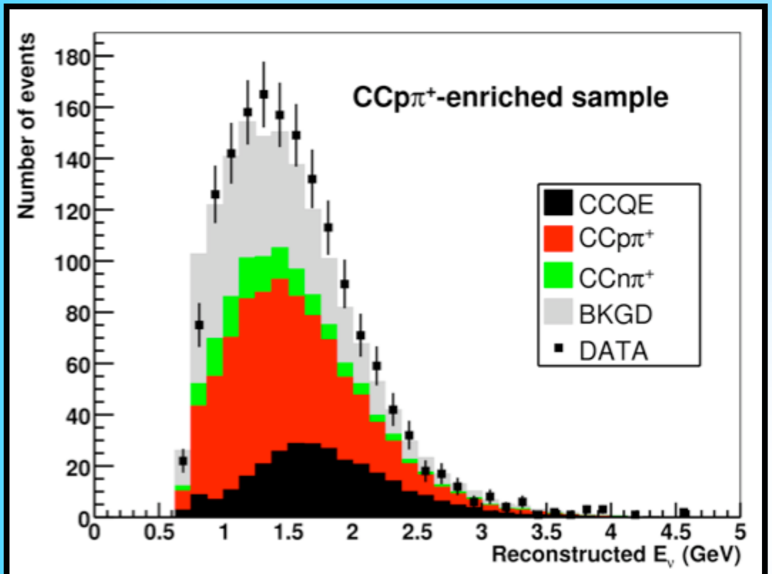
  $\nu_\mu\, n \rightarrow \mu^-\, n\, \pi^+$

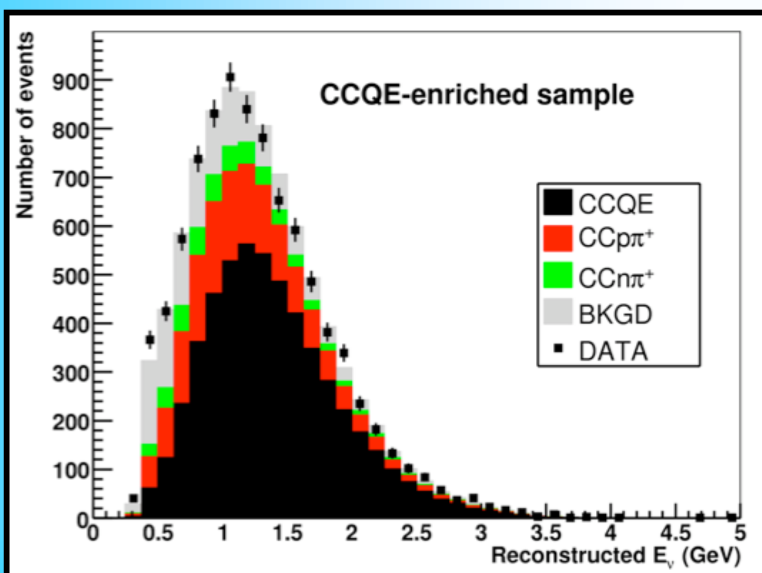
- no existing data on nuclear targets at low energy (E_ν < 3 GeV)

- total statistics ~8,000 events



K2K CC 1π^+ with SciBar Detector





(L. Whitehead, NuInt07)

NEW!

$\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+$

- **1,619 events**
- 41% purity, 13% efficiency

- normalize to QE sample:
  (common approach historically)

$\nu_\mu\, n \rightarrow \mu^-\, p$

- **8,894 events**
- 60% purity, 60% efficiency

K2K CC $1\pi^+$/QE σ Measurements

NEW!

K2K SciBar (^{12}C):

CC $1\pi^+$p/QE σ = 0.614 ± 0.061 (stat) $^{+0.084}_{-0.028}$ (nucl) $^{+0.087}_{-0.077}$ (syst)

(NEUT prediction = 0.565)

CC $1\pi^+$/QE σ = 0.850 ± 0.080 (stat) $^{+0.127}_{-0.039}$ (nucl) $^{+0.119}_{-0.109}$ (syst)

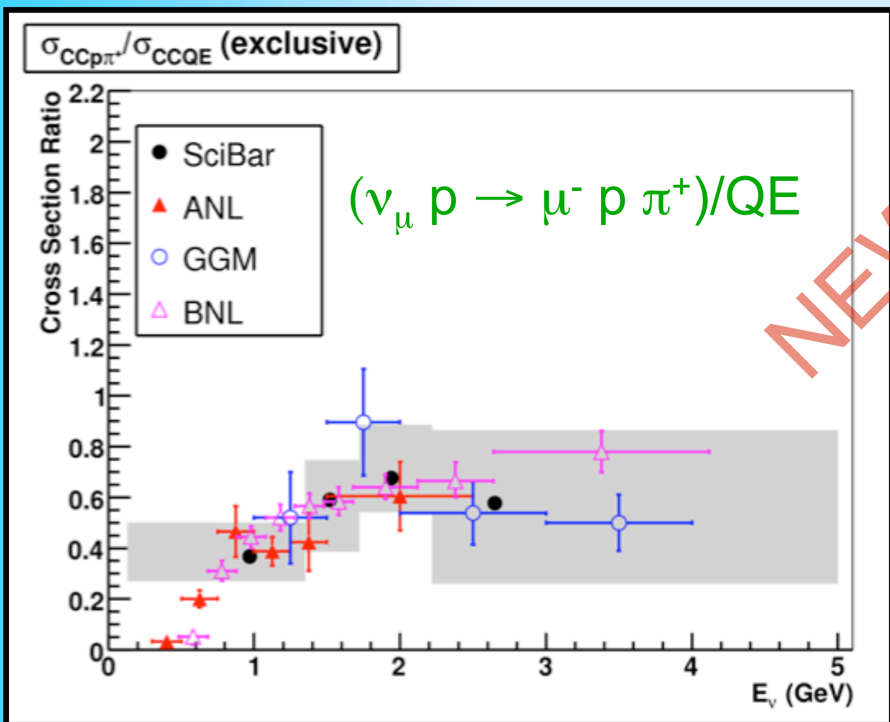
(NEUT prediction = 0.740)

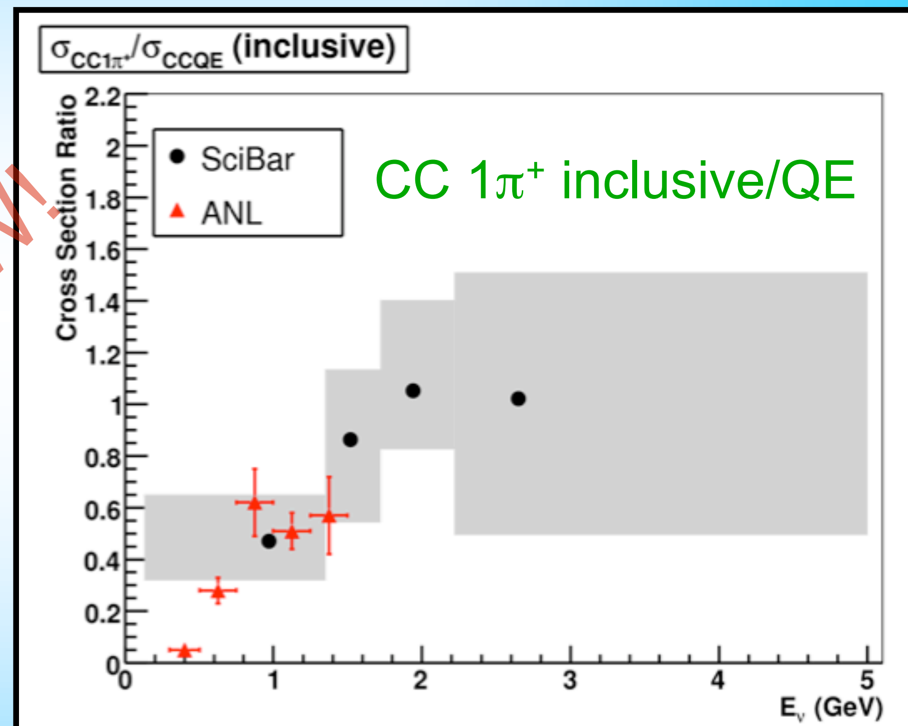
- ~20% measurements
- in good agreement w/ MC prediction
- consistent w/ MiniBooNE prelim results (Wascko hep-ex/0602050)
- measure both total σ and E-dependent σ …

K2K CC 1π^+/QE σ Measurement

- in good agreement with past data …

(L. Whitehead, NuInt07)

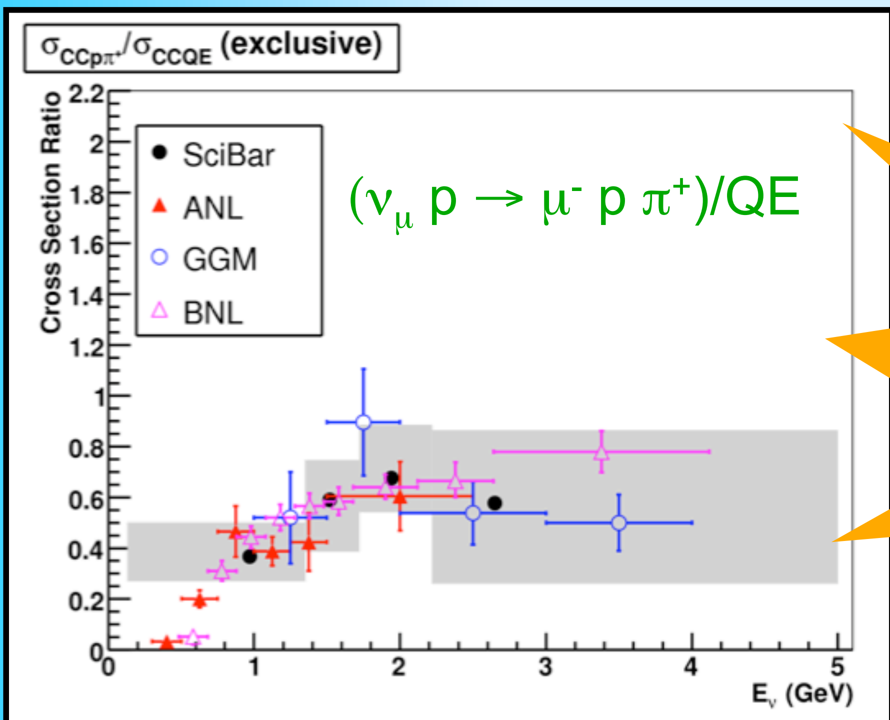




- can repeat with same detector in Booster ν beam (SciBooNE)
  - $\rightarrow$ higher statistics, lower backgrounds
- measure at MINERvA to extend energy region

K2K CC 1π^+/QE σ Measurement

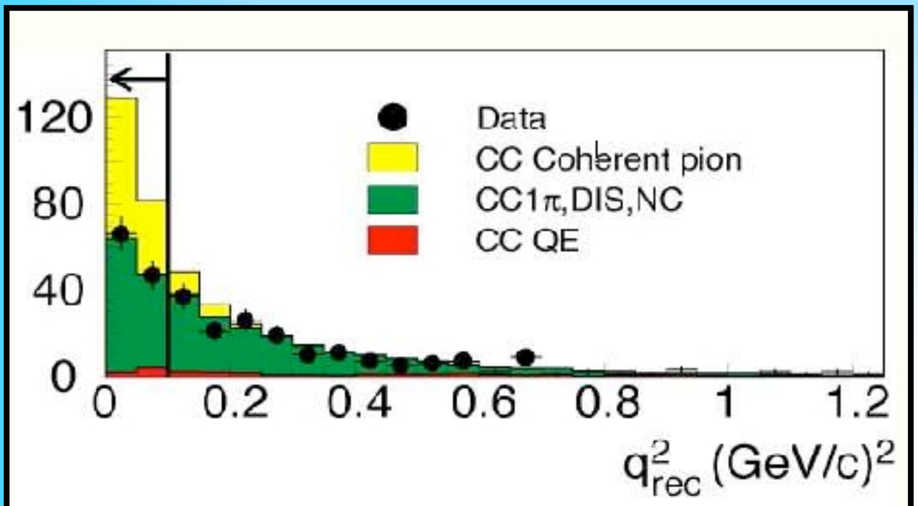
• qualitatively good agreement with past data …



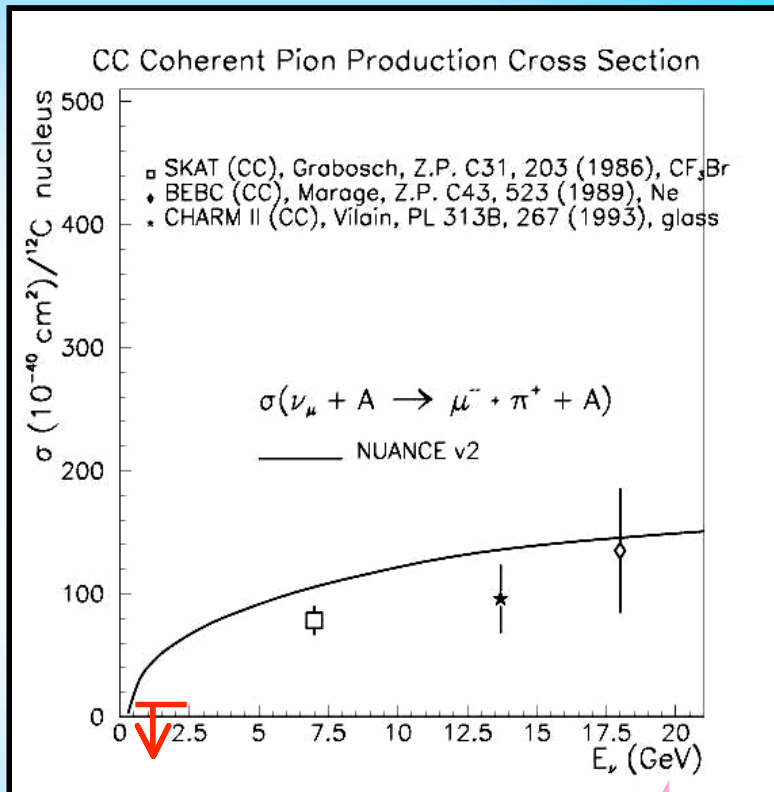
will be important for
T2K ($\Delta m^2,\theta_{23}$)
goal CCπ^+/QE: 5-10%

• how well know non-QE backgrounds & their energy dependence will directly map into uncertainties in Δm^2, θ_{23}

K2K Coherent 1π^+ Production



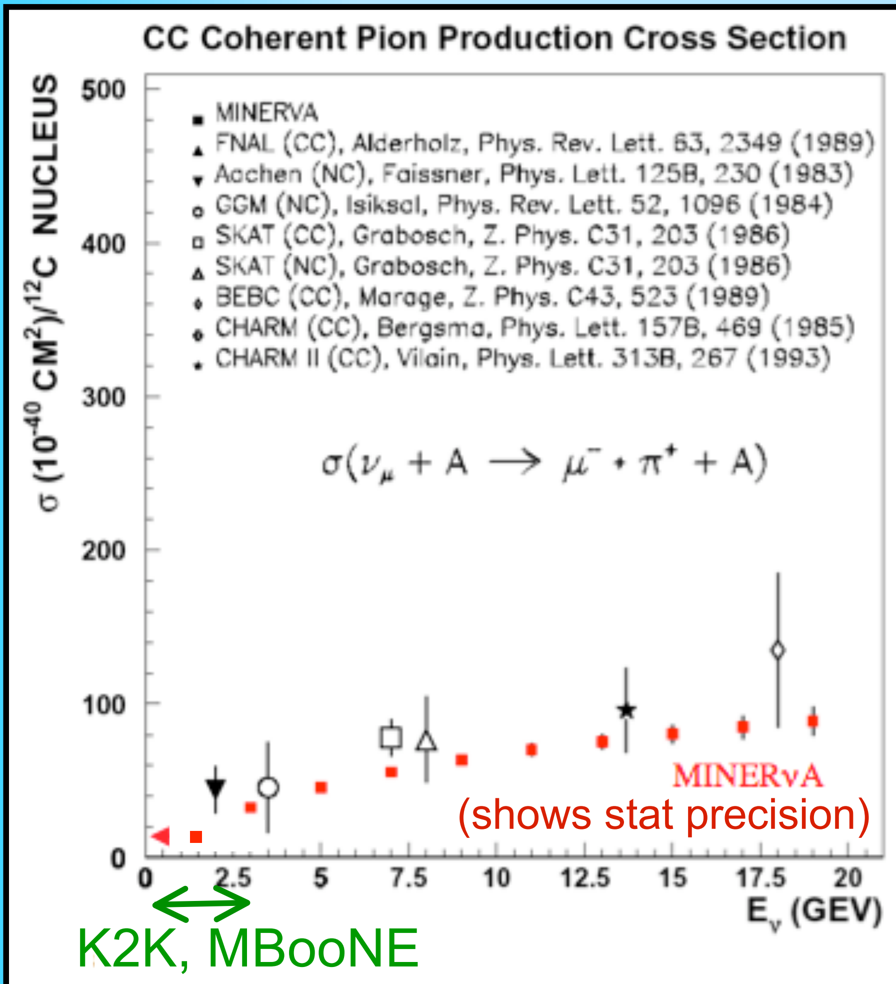
(M. Hasegawa *et al*., PRL**95**, 252301 (2005))



- 1st CC coh π^+ prod results at LE
- somewhat surprising results …

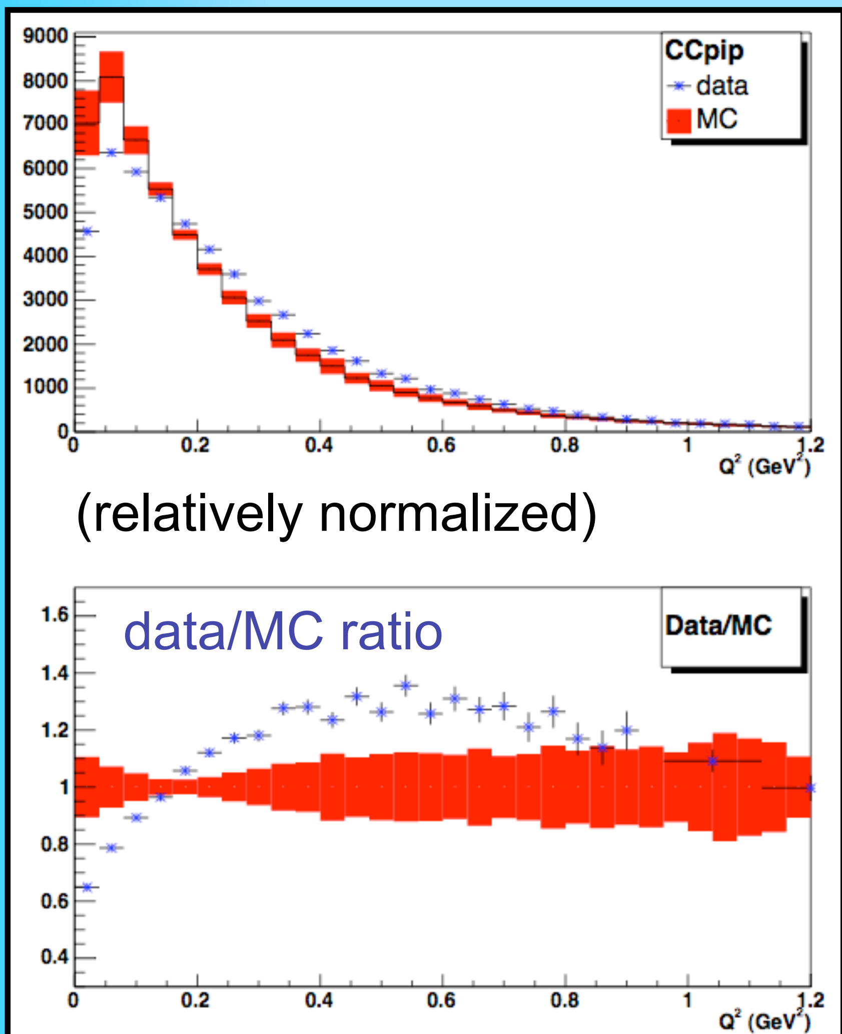
  - see no evidence for coherent π^+ prod, set upper limit
  - MiniBooNE and K2K see evidence for NC coherent π^0 prod
  - NC, CC difference? μ mass effects? (Rein, Sehgal, hep-ph/0606185)

MINERvA to the Rescue



- coherent π production has been a hot topic (many papers)
- will be able to precisely meas coherent σ as fcn of energy
- high statistics
  - 85,000 CC ν+A $\rightarrow$ μ+A+π^+
  - 37,000 NC ν+A $\rightarrow$ ν+A+π^0
- compare coherent σ on variety of nuclei (A-dependence, different model predictions for this)

CC $1\pi^+$ Q^2 Dependence?!



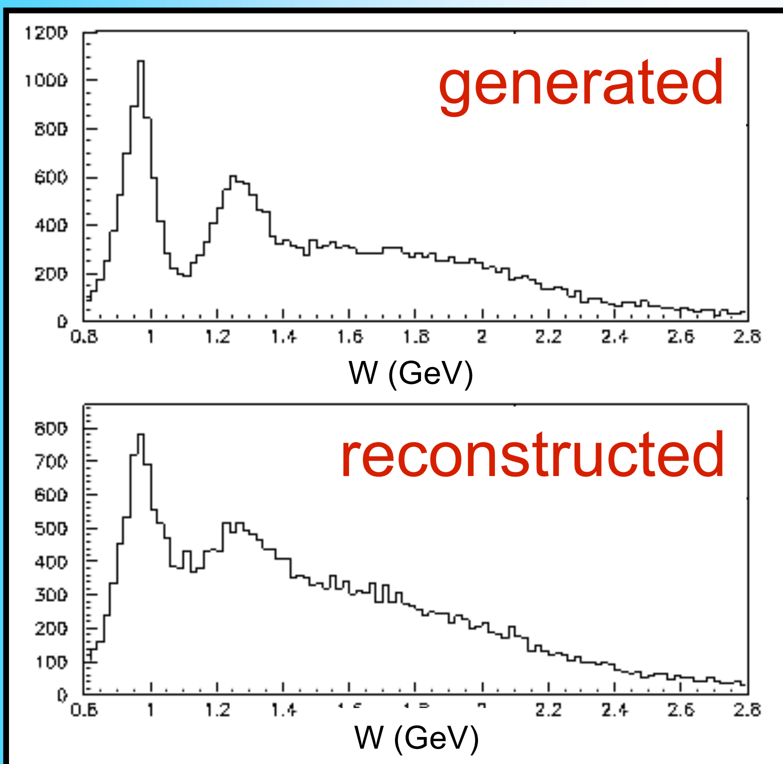
(B. Fleming, J. Nowak, NuInt07)

- in addition to coherent π^+ prod
- new data revealing large inconsistencies in Q^2 dep of resonance CC $1\pi^+$ events ?
  - also seen in other exps
  - and since beginning of NuInt
- **MiniBooNE CC $1\pi^+$ sample**
  - 71,000 events, CH_2
    (order of mag > than all other exp)
- form factors? nuclear effects? coherent π^+? something else?

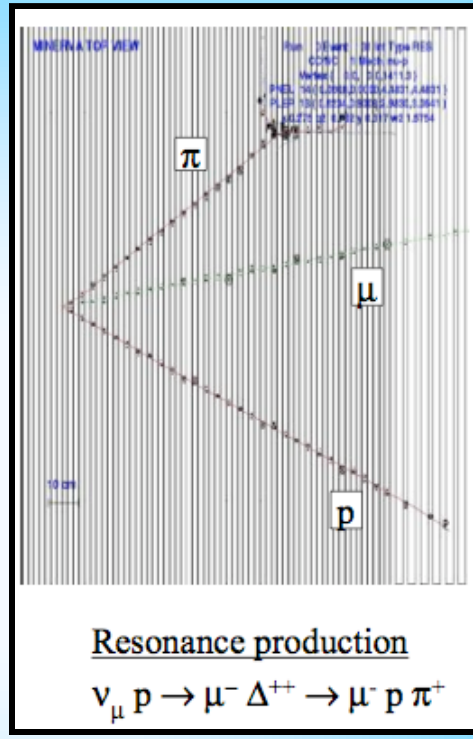
CC $1\pi^+$ Production at MINERvA

- expect 1.2M resonance 1π events

- important to be able to track all of the final state particles



(O. Lalakulich)

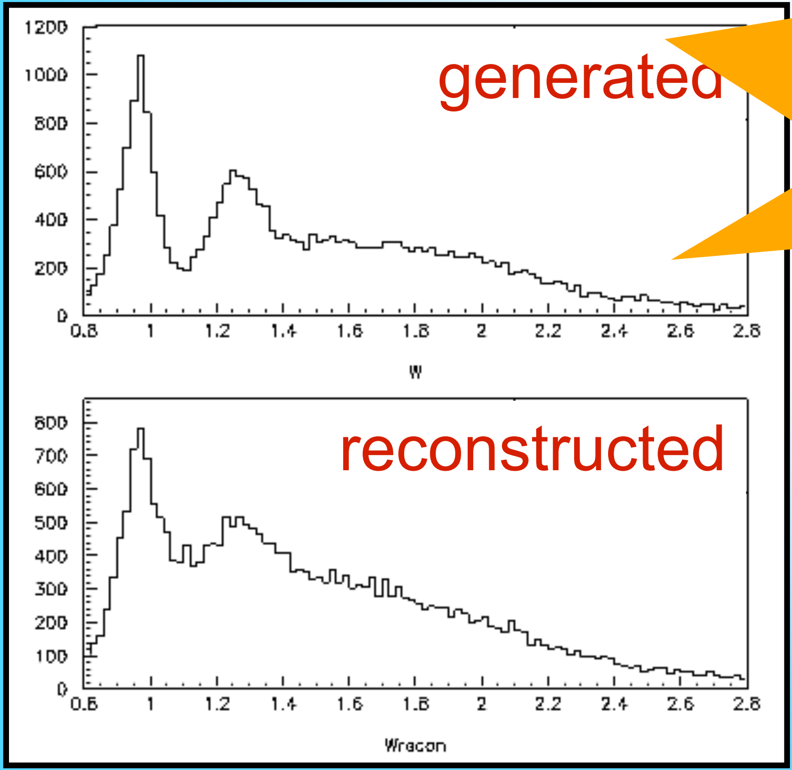


- can reconstruct hadronic mass

  (haven't see this yet in modern data sets)

- have been discussing $\Delta \rightarrow N\pi$ but can also have $\Delta \rightarrow N\gamma$

CC $1\pi^+$ Production at MINERvA



(O. Lalakulich)

important for MiniBooNE $\nu_\mu \rightarrow \nu_e$ oscillation analysis (T2K, NOvA, θ_{13})

- can reconstruct hadronic mass
- opens possibility to measure $\Delta \rightarrow N\gamma$ in neutrinos for 1st time

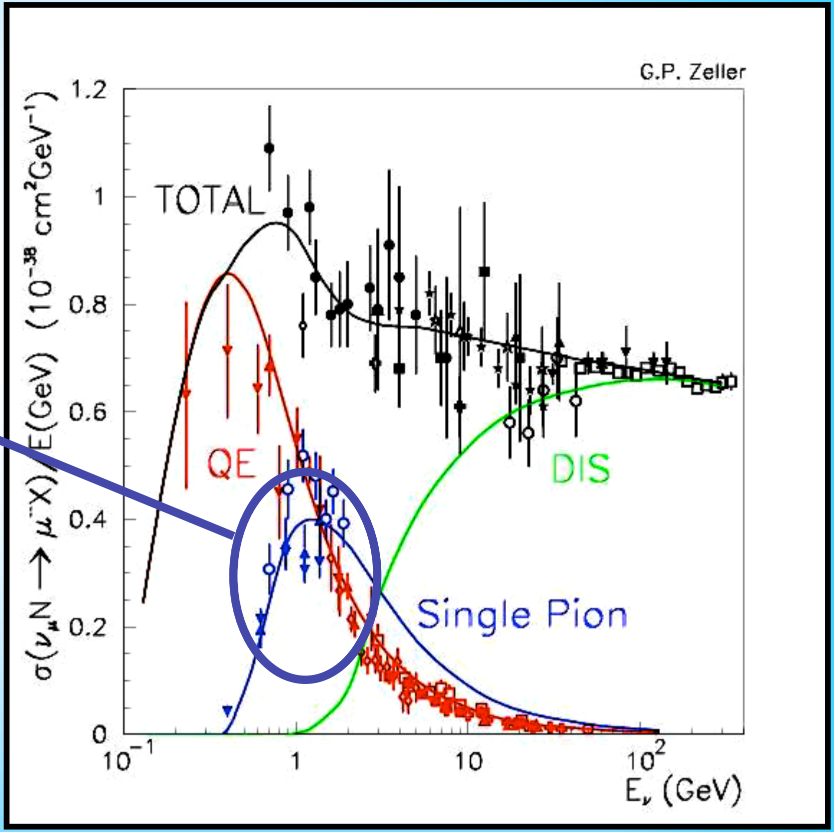
Low Energy Neutino Interactions

• moving on to the next reaction channel …

(1) quasi-elastic (QE)
- dominates $E_\nu \lesssim 1$ GeV

(2) NC, CC 1π production
- NC π^0 (res+coh)
- CC π^+ (res+coh)
- CC π^0 (res)

(3) CC inclusive, DIS
- dominates $E_\nu \gtrsim 5$ GeV

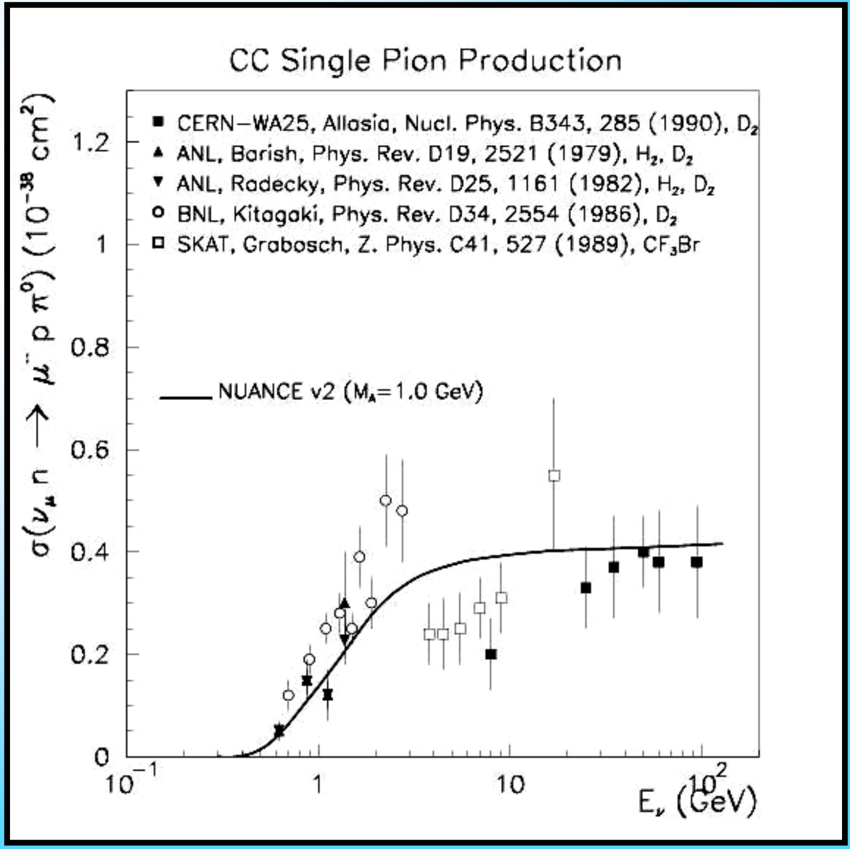


Past CC $1\pi^0$ σ Measurements

- given Q^2 disagreement and questions surrounding coherent production in CC $1\pi^+$ channel, can perhaps gain some insight from CC π^0 samples

  (resonance only)

$$\nu_\mu\, n \rightarrow \mu^-\, p\, \pi^0$$



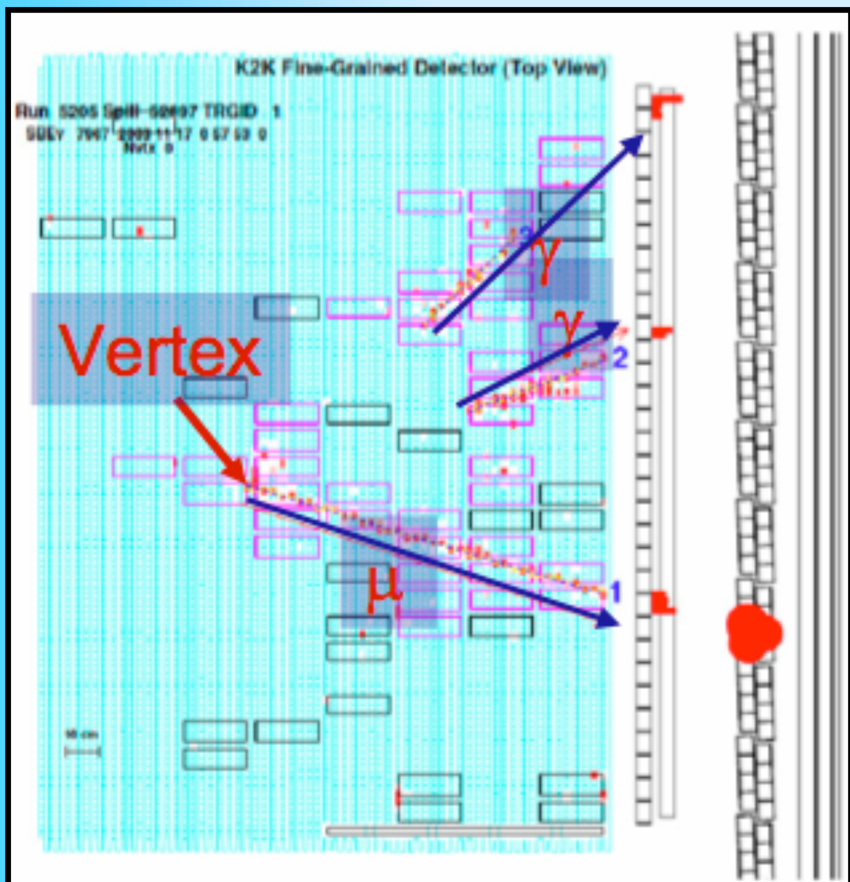
- good example of place where discrepancies exist

- total stats < 2,000 events for all combined

CC π^0 Production at K2K

NEW!

- CC π^0 event in the SciBar detector:



(C. Mariani, NuInt07)

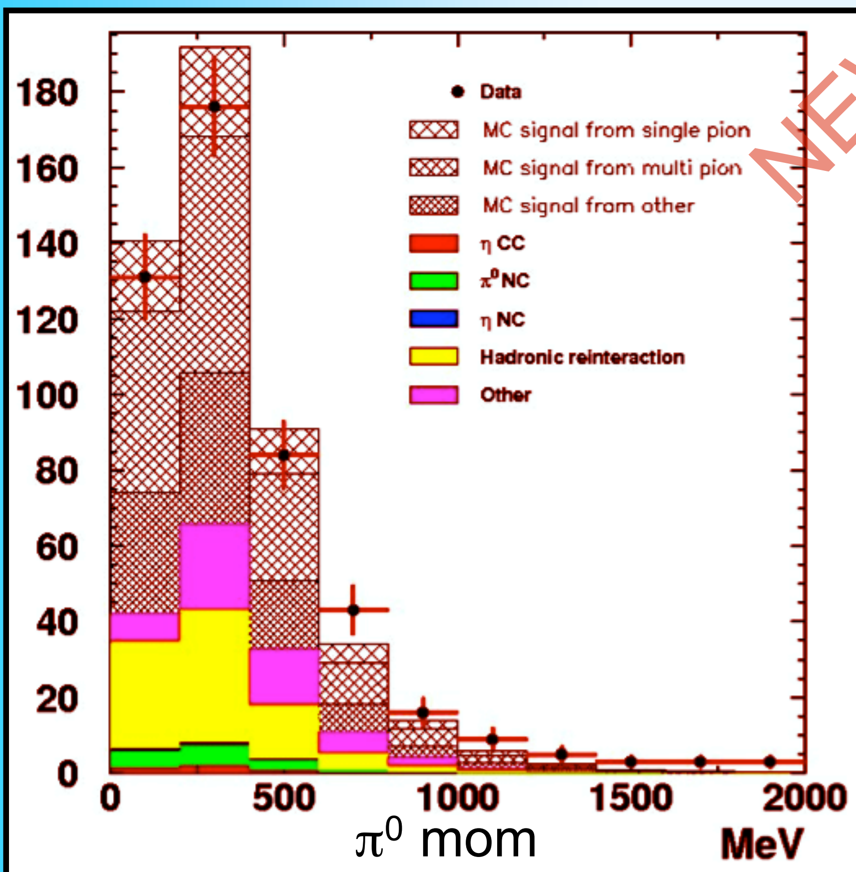
$$\nu_\mu\, n \rightarrow \mu^-\, p\, \pi^0$$

- very 1st look at this reaction in a modern data set!

  - 479 CC π^0 events
  - 59% purity
  - 7.6% efficiency

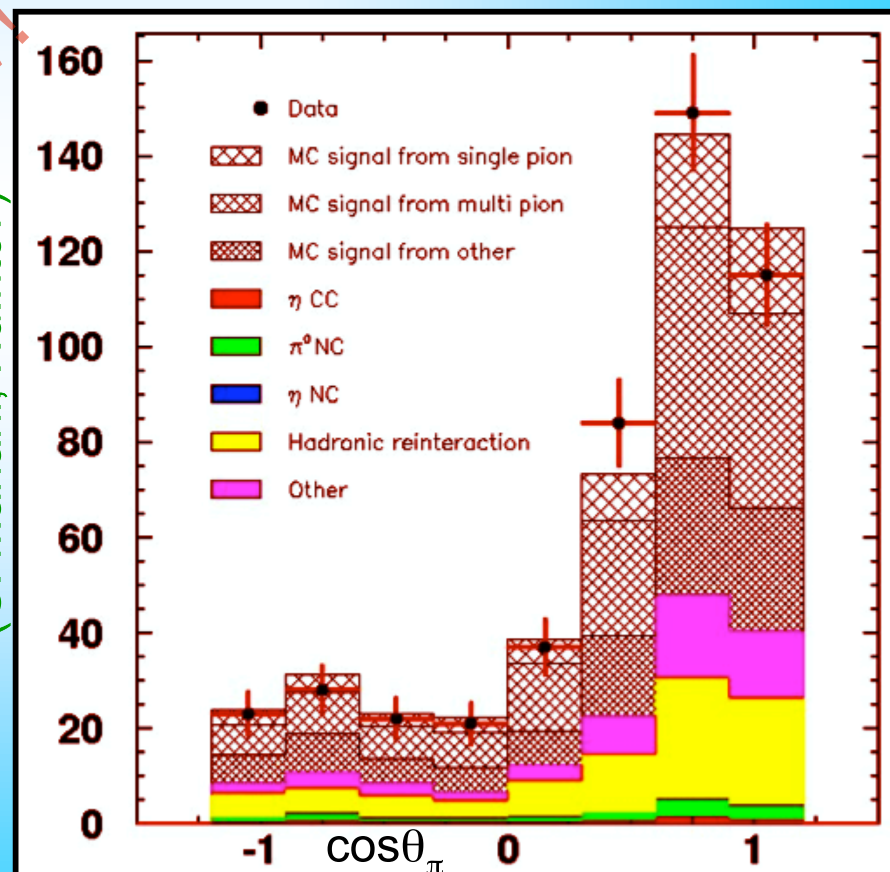
K2K CC π^0 Results

- no coherent scattering component, so probes resonance contrib alone
- venturing into transition region: sample is roughly 1/2 single-π, 1/2 multi-π



NEW!

(C. Mariani, NuInt07)



K2K CC π^0/QE Cross Section

NEW!

K2K SciBar:

$$\text{CC } \pi^0/\text{QE } \sigma = 0.306 \pm 0.023 \text{ (stat)} \;{}^{+\,0.023 \text{ (syst)}}_{-\,0.021 \text{ (syst)}}$$

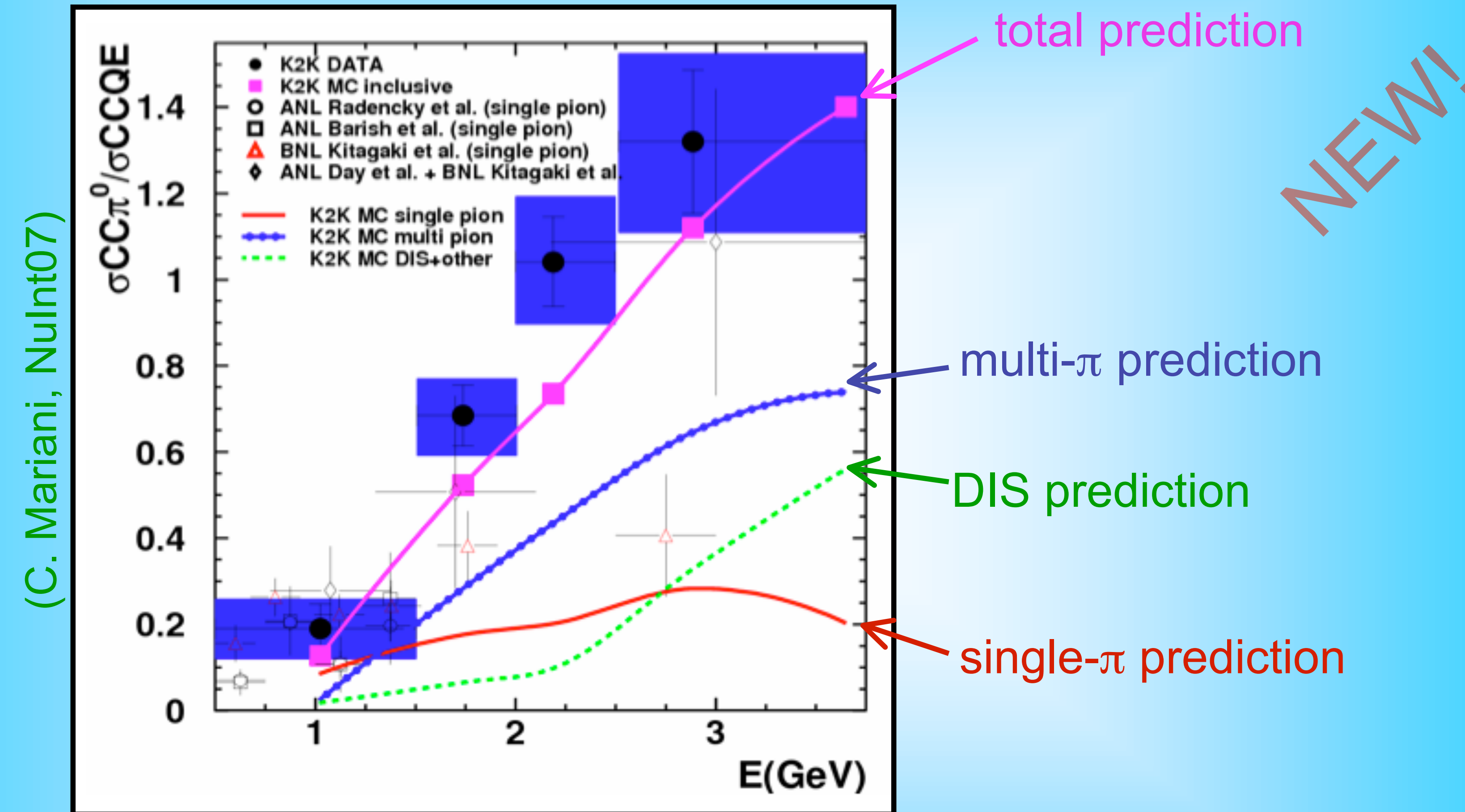
(NEUT prediction = 0.220)

- ~10% measurement
- 1st measurement of CC π^0 on carbon at low energy
- 40% higher than MC prediction

?

- together with agreement in 1π samples, translates into a (30 ± 18)% excess in multi-π cross section

K2K CC π^0/QE Cross Section



- can repeat with same detector in Booster ν beam (SciBooNE)
- will be interesting to measure at higher energy (MINERvA)

shouldn't assume we know!

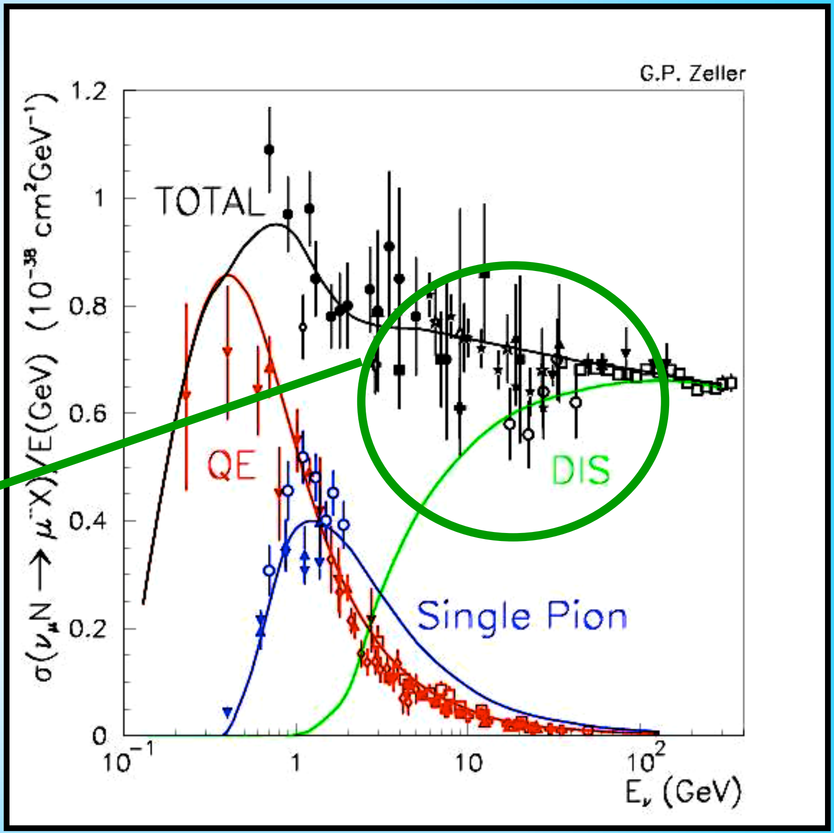
Low Energy Neutrino Interactions

- and finally …

  (1) quasi-elastic (QE)
  - dominates $E_\nu \lesssim 1$ GeV

  (2) NC, CC 1π production

  (3) CC inclusive, DIS
  - dominates $E_\nu \gtrsim 5$ GeV



- "transition region" between QE, DIS difficult to predict & poorly measured

- total σ useful as normalization sample for measuring σ's of other processes

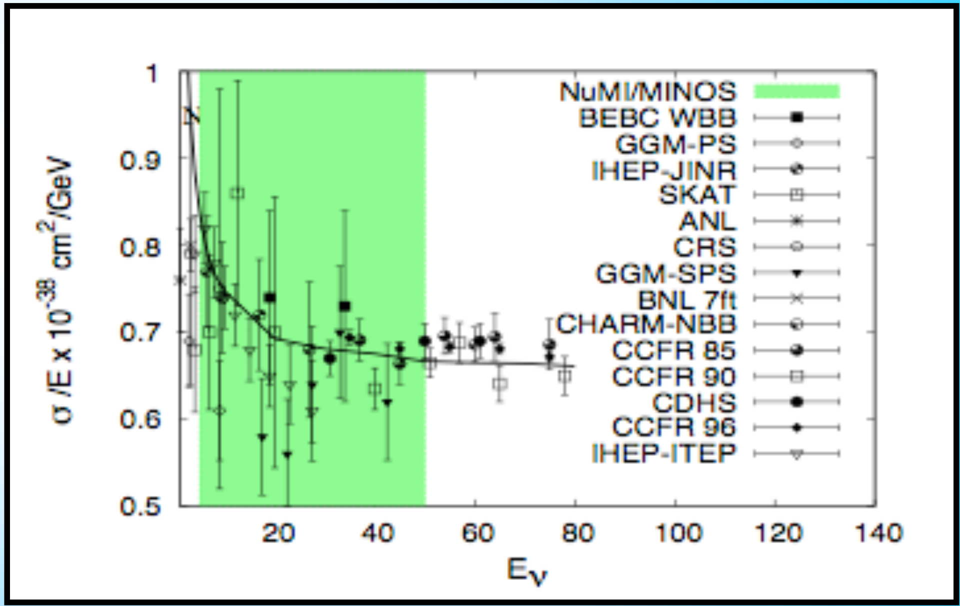
Inclusive Cross Sections

- MINOS and NOMAD cover interesting region where all three processes contribute (QE, RES, & DIS)

  - **MINOS**: 2.1M ν Fe
    0.2M $\bar{\nu}$ Fe (6% WS)

  - **NOMAD**: 1.3M events C

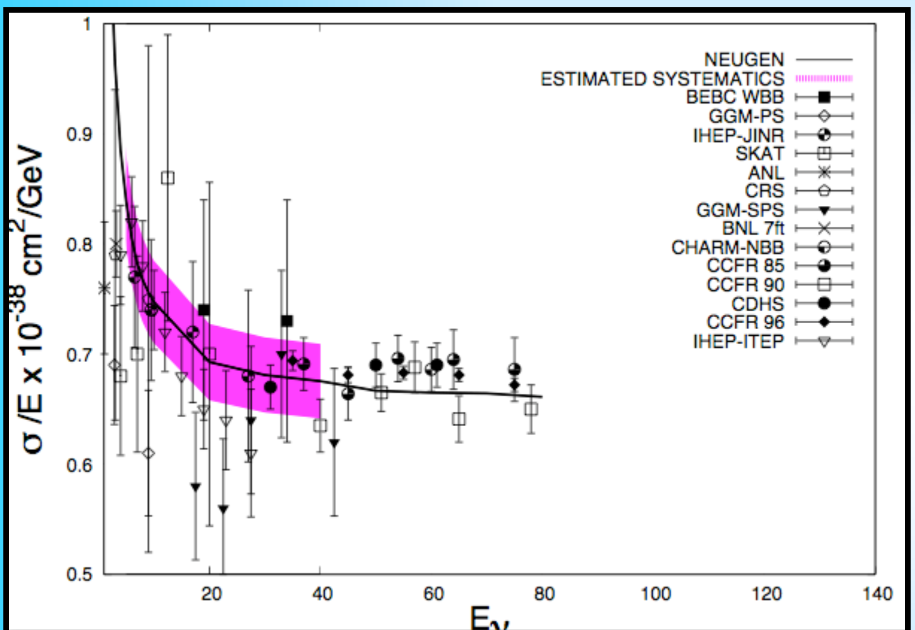
- inclusive σ_ν well-measured at high energy (CCFR, NuTeV)



- less well-known $E_\nu \approx 3$ - 50 GeV
  - existing data of limited precision ($\gtrsim$ 10%)

Inclusive σ_{CC} Measurements

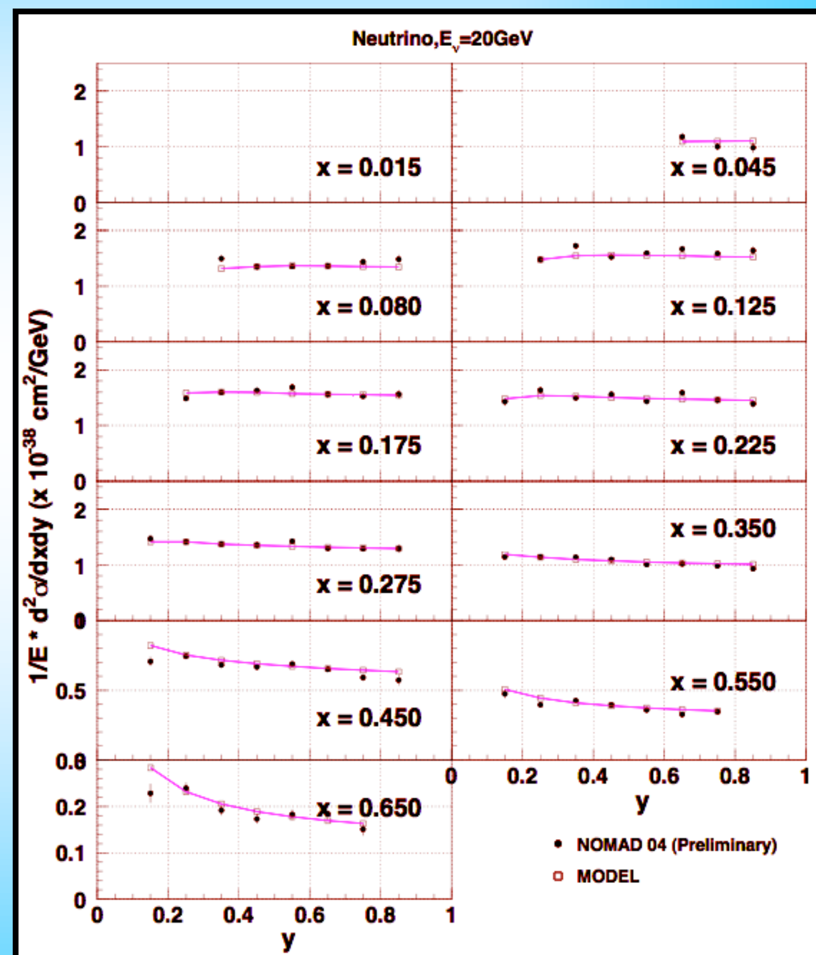
MINOS projection, Fe



(D. Naples, D. Bhattacharya)

- goal: 5% total σ measurement
- $5 < E_\nu < 50$ GeV

NOMAD, ^{12}C, E_ν = 20 GeV

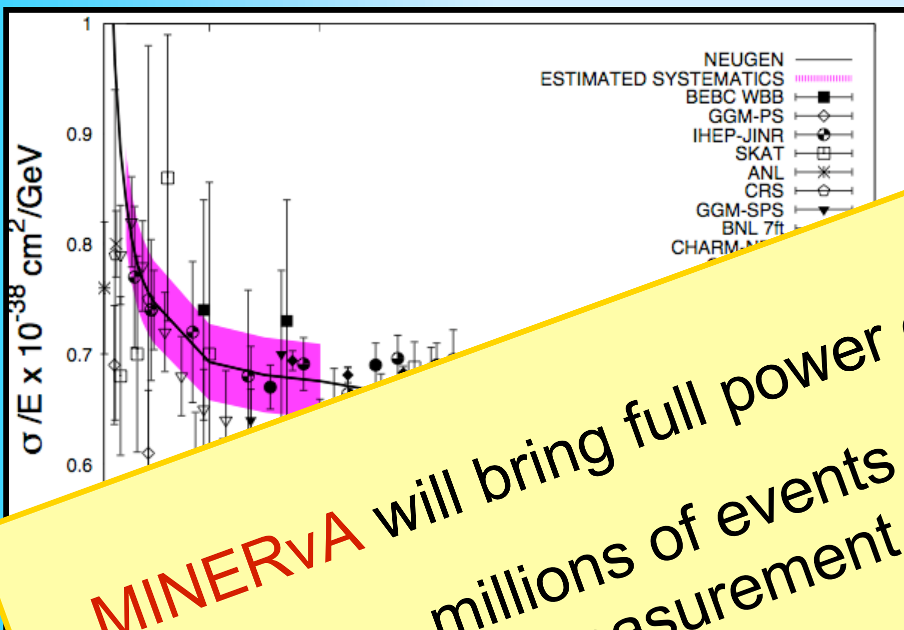


(R. Petti, NOMAD)

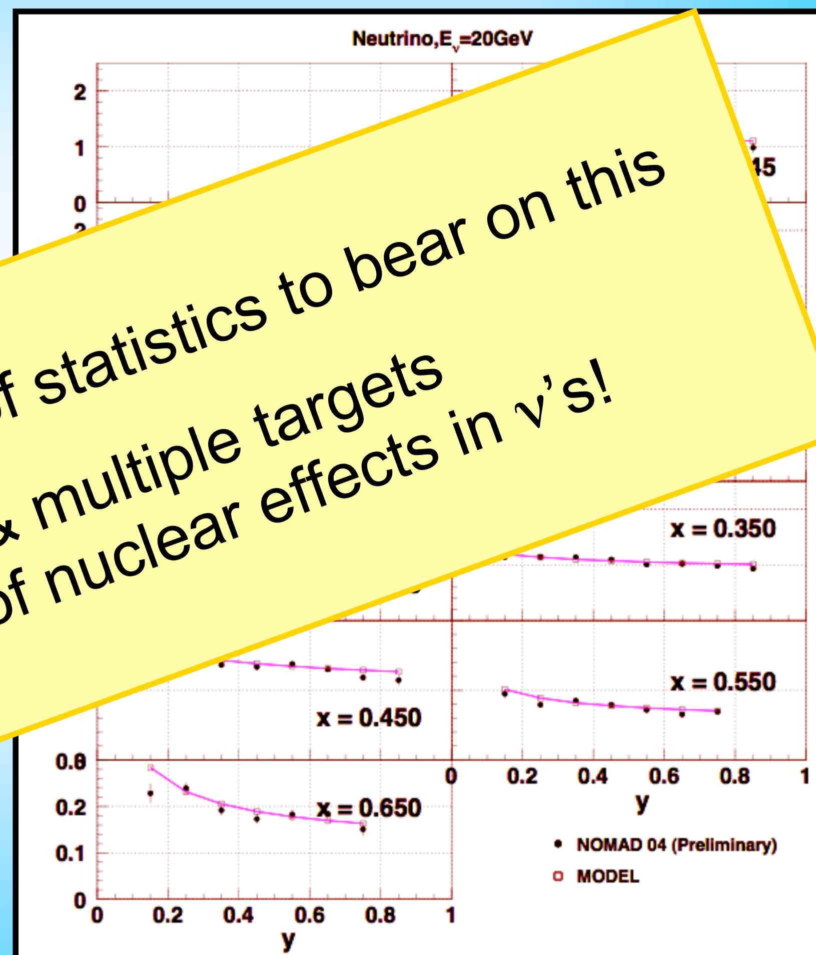
- $6 < E_\nu < 300$ GeV

Inclusive σ_{CC} Measurements

MINOS projection, Fe



NOMAD, ^{12}C, E_ν = 20 GeV



(R. Petti, NOMAD)

MINERvA will bring full power of statistics to bear on this

- millions of events & multiple targets
- 1st ever measurement of nuclear effects in ν's!

	Past	Present	Future
QE signal	15-20%	10% M_A - M_A~1.2 GeV (nuclear effects?)	
NC π^0/QE bkg	25-40%	10% - π^0 mom differences (FSI?)	
CC π^+/QE bkg	25-40%	20% - Q^2 disagreement (?)	
CC π^0/QE	25-40%	10% - 40% higher than MC (multi-π?)	
coherent π bkg	100%	10% NC coh/res π^0 - tension between NC and CC?	
inclusive	>10%	MINOS, NOMAD will fill in	

	Past	Present	Future
QE signal	15-20%	10% M_A - M_A~1.2 GeV (nuclear effects?)	5%
NC π^0/QE bkg	25-40%	10% - π^0 mom differences (FSI?)	<10%
CC π^+/QE bkg	25-40%	20% - Q^2 disagreement (?)	5%
CC π^0/QE	25-40%	10% - 40% higher than MC (multi-π?)	5%
coherent π bkg	100%	10% NC coh/res π^0 - tension between NC and CC?	5-10%
inclusive	>10%	MINOS, NOMAD will fill in	5-10%

+ nuclear effects!

	Past	Present	Future
QE signal	15-20%	10% M - ? Ge ear eff	5%
NC π^0/QE bkg	25		<10%
CC π^+/QE bkg			5%
CC π^0/Q		MC ?)	5%
coherent π bkg	100%	NC res π^0 - t on betwe NC and CC?	5-10%
inclusive	>10%	M NOS, NOMAD will fill in	5-10%

+ nuclear effects!

will have to come back to
this score card in
a few years to see how
this all turned out

Conclusions

- compelling evidence of ν oscillations have increased interest & need for ν σ measurements

- lot of activity in both exp'ly & theoretically in past few years

  - new results from K2K, MBooNE, MINOS, NOMAD
  - 7 new measurements made their debut this week
  - a lot of firsts (many new meas in regions where previously no data)
  - plus, some surprises ?

- continued progress on measuring these input σ's critical for success of future ν oscillation experiments

  - SciBooNE & MINERvA collecting ν data soon!
  - opportunity to make high impact measurements in ν σ's

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